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Responses of Forests to Atmospheric Deposition National Research Plan for the Forest Response Program

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RESPONSES OF FORESTS TO ATMOSPHERIC DEPOSITION

National Research Plan

for the

Forest Response Program

National Acid Precipitation Assessment Program

U.S. Environmetal Protection Agency

U.S. Department of Agriculture -- Forest Service

National Council of the Paper Industry for Air and Stream Improvement

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16. ABSTRACT

This document presents the national research plan for the Forest Response Program. The introduction provides an overview, a statement of the program objective, and a brief description of the program's organizational structure. A Program Foundations section forms the heart of the research plan; it discusses the scientific approaches that will be used to reach the program objective. Program Implementation contains the priorities and research approach used by each component of the program and outlines how planned research relates to the program objective. Program Management discusses the role of national program management and procedures for the operation of the program. Major Products describes the tangible outputs from the program.

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Executive Summary

Background

The Forest Response Program (FRP) is a research program designed to evaluate the response of forests to airborne chemicals. It is sponsored by the National Acid Precipitation Assessment Program (NAPAP) and funded by the Environmental Protection Agency, the U.S. Forest Service, and the National Council of the Paper Industry for Air and Stream Improvement (NCASI).

Recent reports of dieback and reduced growth in eastern forests have captured public concern and resulted in a call to resolve the question of the role of atmospheric deposition in forest decline. Atmospheric deposition is the deposition of chemicals from the atmosphere to the natural surfaces. It can be wet or dry, and acidic or non-acidic. Forest decline is a reduction in growth and possible death of many individual trees over a large geographic region. Such a decline would have far-reaching effects on the forest ecosystem. A wide array of hypotheses on cause and effects of reported declines have been proposed, but we have no definitive answers.

Objective

The objective of the FRP is to provide information that can be used to address three broad questions related to environmental policy. The approach to addressing these questions is to translate them into more specific questions that can be addressed scientifically. Priorities within each of the three policy questions are based on the most pressing issues currently facing

decision makers. Top research priority has been assigned to questions involving the potential role of sulfur compounds in forest decline. Other pollutants, in their order of priority, are nitrogen compounds, H^+, metals, O_3, H_2O_2, and hydrocarbons. The three policy questions (P.Q.) and their related scientific questions (S.Q.) are listed below. This listing is not meant to preclude addition of other policy or scientific questions as changing circumstances dictate nor are the questions stated in order of priority. The program is designed to be as flexible as possible consistent with rapidly achieving overall objectives.

P.Q. 1: Is there a significant problem of forest damage in North America which might be caused by acidic deposition, alone or in combination with other pollutants?

S.Q. 1.1 Are changes in forest condition greater than can be attributed to typical trends and levels of natural variability?

S.Q. 1.2 What spatial patterns exist in forest condition and how do these patterns relate to spatial patterns of pollutant exposure?

P.Q. 2: What is the causal relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?

S.Q. 2.1 What is the effect of sulfur and/or nitrogen pollutants on forests through the mechanisms of:

(1) Direct toxicity to roots, mycorrhizae, or soil microbial populations by mobilized metals in acidified soil water;

(2) Nitrogen toxicity to mycorrhizae;

(3) Increased leaching of soil nutrients resulting in reduced nutrient availability.

S.Q. 2.2 Increased leaching of foliar nutrients?

S.Q. 2.3 Altered photosynthesis, respiration, and carbon allocation patterns (e.g., morphology) with possible induction of water and/or nutrient stress?

S.Q. 2.4 Delayed cold hardening or early break in dormancy resulting in increased winter damage?

S.Q. 2.5 Disrupting reproduction or regeneration?

S.Q. 2.6 Altered susceptibility to pests and pathogens?

P.Q. 3: What is the dose-response relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?

S.Q. 3.1 What is the dynamic response of forests to specified levels of acidic deposition, alone or in combination with other pollutants?

Strategy

We have distinguished two major conceptual approaches to the study of the effect of atmospheric deposition on forests: (1) the epidemiological approach; and (2) the physiological/ecological approach. We will use both approaches in research on the problem. The epidemiological approach is characterized by broad surveys of forest condition and a search for patterns of condition that may be related to atmospheric deposition or other environmental patterns. The physiological/ecological approach is characterized by more focused experiments on the effects of particular environmental variables on the health of individual trees or stands. Epidemiological studies may uncover spatial or temporal patterns which suggest particular hypotheses to be tested in a physiological or ecological study. Similarly, experimental research may identify a parameter

related to pollutant exposure that can be used in surveys. Initial studies will concentrate on geographic areas of reported concern. The estimation of regional results will be achieved through models which combine physiological and ecological processes with forest dynamics. We also stress the need for early interaction of all research components to guide in the design of future research at all levels.

Physiological and ecological studies will be used to quickly eliminate as many proposed hypotheses as possible by analysis of both existing and newly collected data. This will allow us to target our research efforts and resources on more intensive studies of hypotheses that cannot be readily eliminated. The intensive studies will be planned to determine cause and effect relationships and to quantify tree response.

Program Structure

Research is stratified by major forest types to help focus on specific sets of questions, problems, and symptoms that are typical of a particular forest type. A Research Cooperative has been formed for each of four major forest types.

The Research Cooperatives form the organizational framework of the Forest Response Program. A Research Cooperative is defined here as an interdisciplinary organization of scientists with expertise and responsibilities related to a particular forest type. In addition to the four forest type cooperatives, additional program components have been established. The cooperatives are: Spruce-Fir Research Cooperative, Southern Commercial Forest Cooperative, Western Conifers Cooperative, and Eastern Hardwoods Cooperative. The remaining program components consist of the National Vegetation Survey, the Atmospheric

Exposure Cooperative as well as Quality Assurance and Synthesis and Integration.

Major Products

The FRP will generate five major integrated products. They are listed below with their estimated completion dates.

Table 1. Major products and estimated completion dates.

	Product	Estimated Completion Date
1.	Evaluation of the extent and magnitude of recent changes in forest condition.	12/88
2.	Evaluation of the role of non-air pollution factors in growth reduction and visible decline.	12/88
3.	Quantitative estimates of seedling response to sulfur, nitrogen and associated pollutants at ambient conditions.	12/87, then annually
4.	Evaluation of the roles of sulfur, nitrogen, and associated pollutants in forest damage.	04/89, 04/91
5.	Projection of forest response to alternative deposition levels.	12/91

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1.0 INTRODUCTION

This document presents the national research plan for the Forest Response Program (FRP). The Introduction (1.0) provides an overview, a statement of the program objective, and a brief description of the program's organizational structure. A Program Foundations (2.0) section forms the heart of the research plan; it discusses the scientific approaches that will be used to reach the program objective. Program Implementation (3.0) contains the priorities and research approach used by each component of the program and outlines how planned research relates to the program objective. Program Management (4.0) discusses the role of national program management and procedures for the operation of the program. Finally, Major Products (5.0) describes the tangible outputs from the program.

1.1 Overview

The Acid Precipitation Act of 1980 (Title VII of the Energy Security Act, P.L. 96-294) established the Interagency Task Force on Acid Precipitation to develop and implement a long-term comprehensive national research program. Prior to passage of the Act, several federal agencies were sponsoring acid rain research, but not as a coordinated program. The Acid Rain Coordinating Committee (ARCC), established prior to the Act, was an attempt to organize the ongoing federal efforts. After the Act passed, the ARCC was reconstituted and provided the foundation upon which the statutory National Acid Precipitation Assessment Program was established.

The goal of the National Acid Precipitation Assessment Program (NAPAP) is to develop and maintain a comprehensive information base on the causes and effects of acidic deposition and to provide methods for effective management of the problem. The program includes research, monitoring, and assessment activ-

ities that emphasize the timely development of a firmer scientific basis for decision making by legislators, regulatory officials, resource managers, private sector decision makers, environmental groups, and the public. The NAPAP administers interrelated projects in a variety of research categories including natural emission sources, man-made pollutant sources, atmospheric processes, deposition monitoring, aquatic effects, terrestrial effects, effects on materials, and control technologies. Hundreds of scientists in government, academia, and the private sector are involved in NAPAP activities.

National Acid Precipitation Assessment Program research on the terrestrial effects of acidic deposition is planned and managed through Task Group V, Terrestrial Effects. The U.S. Forest Service (USFS), U.S. Environmental Protection Agency, the U.S. Department of Energy, the Cooperative States Research Service, the U.S. Park Service, and U.S. Geological Survey are all members of Task Group V.

Task Group V's research effort on forest decline and air pollution was relatively limited through FY 1984. It had been largely focused on the response of trees to the direct and indirect effects of acid inputs, especially with sulfate as the major anion. The hypothesized mechanisms of damage developed in Europe and the U.S. have required the NAPAP to broaden its research outlook beyond "acid rain" and to consider nitrates, oxidants, organic compounds, and trace metals as possible pollutants of interest.

There is a need for coordinated management and funding of a national, integrated research program. In response to this need, the USFS and EPA have negotiated an interagency agreement that establishes the management structure, the competition and peer review requirements, and the funding levels for coordination of the Forest Response Program. The National Council of the Paper Industry for Air and Stream Improvement (NCASI) is also an active participant

and funding contributor to the FRP. Thus, this research program is a highly integrated interagency program.

Natural forest ecosystems in the United States have been subjected to elevated levels of air pollutants for several decades because of regional scale industrialization and urbanization. The pollutants include both gaseous and acidic deposition. At present, the effects of these pollutants have not been quantified except for the effects of O_3 on trees in southern California and on eastern white pine. There are extensive data on the concentrations of the gaseous pollutants (SO_2, NO_x, and O_3) required to cause visible injury to plant foliage and to cause plant mortality. However, little is known about effects of derived pollutants (H^+, NO_3^-, $SO_4^=$) on plant growth and yield from current exposures in large areas of the United States. Even less is known about the interactive effects of these pollutants.

There is little documentation of the effects of pollutants on forest trees because of their size and perennial nature. This makes it difficult to conduct short-term manipulative experiments. The effects of pollutants can be expected to be subtle and chronic as a result of their relative levels and characteristics of deposition on forests. Pollutant response may also occur simultaneously with natural stresses and thus may be difficult to isolate. However, these subtle responses must be studied because of the economic and ecological importance of the forests in regions currently exposed to acidic deposition and other anthropogenic pollutants.

There is no conclusive scientific evidence indicating that acidic deposition is limiting growth of plants in forests in either Europe or the United States. Reports from several sources, however, suggest that forest tree growth is decreasing, principally in some coniferous species in some areas of the U.S. and in Europe. A growth decline in high elevation red spruce in the eastern

U.S. since the early 1960's has been reported for fixed plot surveys performed in the early 1980's (Johnson, 1983). Growth declines since the 1950's and 1960's in several species of southern commercial pine have been recently demonstrated in a report of Forest Service Forest Inventory and Analysis data for the southern U.S. (Sheffield et al., 1985). There are also reports of forest dieback and growth decline of several conifer and hardwood species in the Federal Republic of Germany (FRG). The relationship of these changes with possible gradients of atmospheric deposition has evoked public concern that atmospheric pollutants may be involved. The Forest Response Program was established by the EPA, U.S. Forest Service, and NCASI to address these concerns.

1.2 Program Objective

The objective of the Forest Response Program is to provide information that can be used to address three broad questions related to environmental policy:

1. Is there a significant problem of forest damage in North America which might be caused by acidic deposition, alone or in combination with other pollutants (e.g., SO_x, NO_x, O_3, H^+, metals, H_2O_2, or hydrocarbons)?
2. What is the causal relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?
3. What is the dose-response relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?

These questions represent the desires of federal policy makers to resolve the acidic deposition debate. Their wording is the result of an iterative process among representatives of EPA, the U.S. Forest Service, and NCASI. As we learn more about the effects of air pollutants on forests, however, new policy questions may arise. If so, this research plan will be updated to address the new policy questions.

Because it exists to address specific questions, the FRP must be considered an applied, goal-oriented research program. Basic research may be undertaken as necessary to further the work of the program, but the overriding focus will always be to address the policy questions.

1.3 Program Organization and Rationale

The FRP is stratified by major forest types to help focus on specific sets of questions and problems that are typical of a particular forest type. A Research Cooperative has been formed for each of four major forest types. A Research Cooperative is defined here as an interdisciplinary organization of scientists with expertise and responsibilities related to a particular forest type. In addition to the four forest research cooperatives, a National Vegetation Survey and an Atmospheric Exposure Cooperative have been formed and are treated as cooperatives. A Forest Team (FT) has been organized to support centralized planning and technical management. A brief rationale for each of these organizations is listed below:

Spruce/Fir: Forest decline symptoms have been identified both in the northern and southern Appalachians. In some areas, severe dieback and mortality in red spruce have been reported.

Southern Commercial Pines: These areas represent the major commercial forest lands in the eastern U.S. Some evidence of unexplained growth reductions

has been reported in USFS surveys. Visible foliar damage due to elevated ozone is a common occurrence on certain species.

Eastern Hardwoods: Oak/hickory and maple/beech/birch stands comprise the majority of the hardwood forests in North America. Oak/hickory forests cover a large area of the eastern U.S. and oxidant damage has been reported in this forest type (e.g., western white pine). Beech was the first hardwood to develop decline symptoms in Germany. In the U.S., there is no visible evidence of effects of atmospheric deposition; however, beech bark disease caused widespread mortality and decline in northeastern forests.

Western Conifers: Oxidant damage has been identified in some western forests. Rapid population growth and development may increase pollutant loads in the future.

National Vegetation Survey: Full documentation of the extent and magnitude of damage symptoms is not yet available. The importance of this documentation necessitates a strong survey component to the Forest Response Program. Development of appropriate stratification and techmical procedures for both inventorying and monitoring of forest ecosystems is underway. Recommendations for the implementation of regional forest ecosystem monitoring will be prepared. Implementation will not begin until appropriate methodology and funding have been identified.

Atmospheric Exposure Cooperative: This group will provide air quality and deposition monitoring support to the other Research Cooperatives as needed and will work with the Cooperatives to identify regional pollutant exposure levels.

Forest Team: This team has been formed to facilitate coordination within the program. The FT will serve as a focal point for national-level planning

and program review, quality assurance, centralized data management, information exchange, and program-wide assessments. Its component parts are Synthesis and Integration and Quality Assurance:

Synthesis and Integration Project: The S&I Project has primary technical responsibility for generating the five major integrated products of the FRP. The S&I Project will address S.Q. 3.1 to provide quantitative estimates of forest response to acidic deposition and associated pollutants. The project has the long-term goal of providing a framework under which forest response can be estimated under alternative deposition scenarios.

Quality Assurance Program: The QA Project is responsible for providing guidance and resources to investigators for the implementation of a Quality Assurance (QA) Program that assures comparability of data across sites and over time through: (1) the standardization of research and QA techniques; and (2) the monitoring of research projects to assure compliance with standard or approved protocols. Ultimately, they provide evidence of data quality through qualitative and quantitative evaluations of the research activities. The specifics of these responsibilities are outlined in a separate Quality Assurance Implementation Plan.

Each Research Cooperative will provide the programmatic structure needed to carry out its specific goals and objectives, and to contribute to the goals and objectives of the entire FRP. The interrelationships of these program components are illustrated in Figure 1. A detailed discussion of the management structure and responsibilities is contained in Section 4.0.

Four types of research activities are sponsored by the FRP. They include: (1) scientific literature reviews/analysis of existing data; (2) controlled

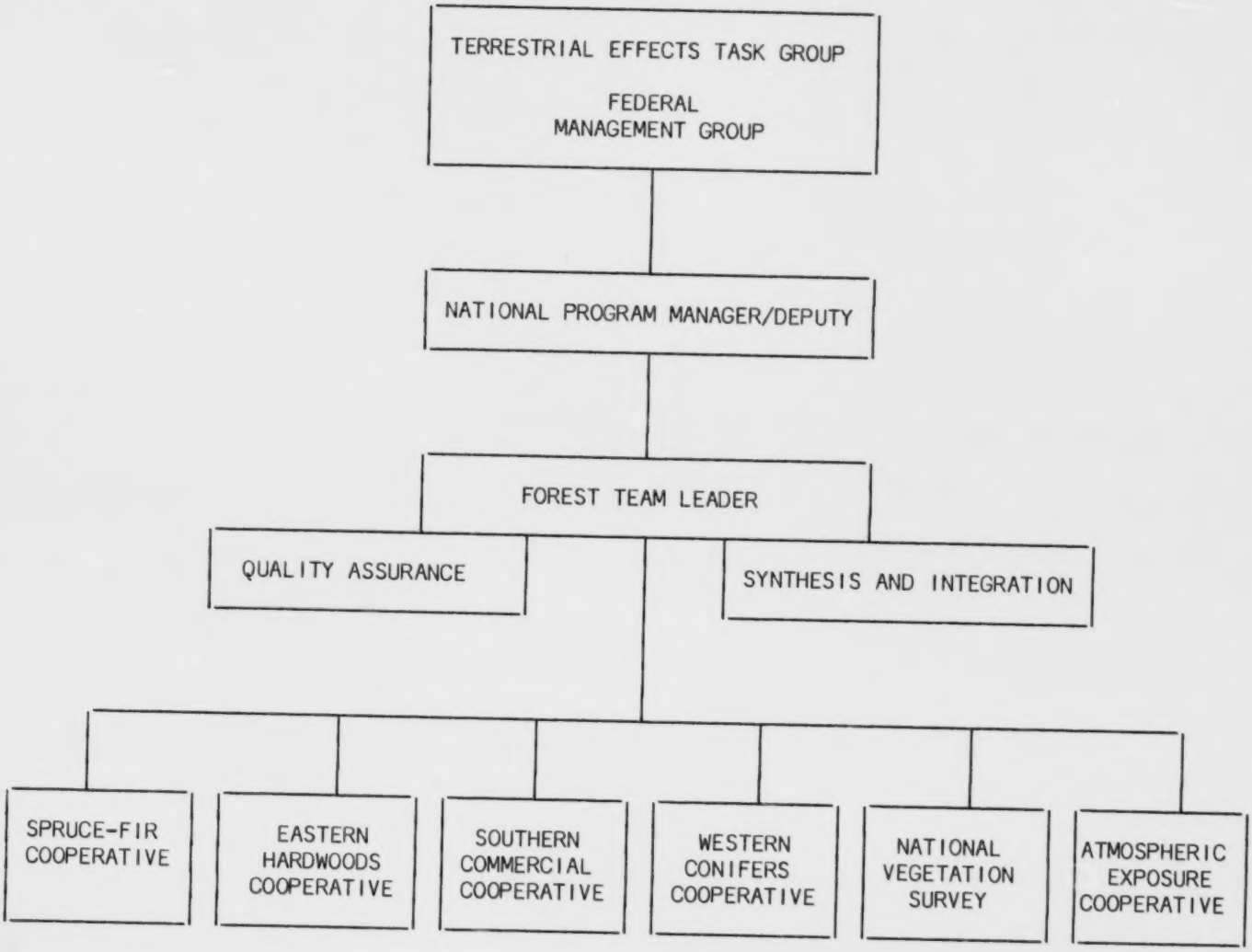

Figure 1. Organizational structure of the Forest Response Program. Appendix A contains the names and addresses of current staff.

laboratory, greenhouse, and field studies applying or excluding atmospheric pollutants; (3) field surveys of forest condition; and (4) development/application of forest models to predict response to pollutants. These activities reflect the strategy for research in the FRP and will be described further in Section 2.0.

1.4 Coordination with Other Programs

The work of the Forest Response Program will be coordinated with the following research efforts within NAPAP and related organizations.

Forest Industry Research Programs

In 1984, a task group of forest industry scientists was formed by the National Council of the Paper Industry for Air and Stream Improvement (NCASI), the research arm of the industry, to review information about the effects of air quality on forest productivity in North America. The task group concluded that there is no evidence of a widespread decline in forests that can be attributed to air pollution. Yet the possibilities that pollution may negatively affect tree growth cannot be ruled out without a substantial research effort. A 5-year research program was developed in 1985 to pursue five long-term goals: (1) to determine ambient air quality in commercial forest lands; (2) to define responses of major tree species to ambient concentrations of air pollutants; (3) to define impacts of ambient air quality on productivity of commercial forest land; (4) to participate in cooperative research projects; and (5) to define impacts of atmospheric deposition on forest soil productivity.

Electric Power Research Institute

The Electric Power Research Institute (EPRI) currently supports several projects studying the effects of acidic deposition and air pollution on forests. A major project undertaken by the EPRI's Ecological Studies Program, the Integrated Forest Study, will investigate the role of acidic deposition in producing changes in forest nutrient cycling, with special attention to areas of forest dieback. Field research will be conducted at thirteen forest sites (eight intensive) in New York, North Carolina, Tennessee, Georgia, and Washington. The project will attempt to answer these questions: (1) How is acidic deposition modified by forest canopies? (2) How are soil nutrients affected by canopy throughfall? (3) What is the relationship between atmospheric and canopy concentrations of dry deposition?

NADP/NTN Network

The National Acid Deposition Program/National Trends Network (NADP/NTN) of wet deposition monitors provides another opportunity for close coordination of research efforts. The NADP has sought to establish new collection sites at locations where significant forestry and agricultural effects research was being conducted. This policy of co-location of collection sites will be continued as new experimental sites of reasonable permanence are developed. The ultimate goal of coordination with the NADP/NTN network is to obtain adequate and reliable measurements of wet deposition and air quality on biologically relevant scales at all forest effects research sites.

Watershed Research

The USFS, EPA, Department of Energy (DOE), National Park Service (NPS), Tennessee Valley Authority (TVA), and National Science Foundation (NSF) all

sponsor extensive watershed research programs. An expansion of the EPA program will focus primarily on testing models of the processes in watersheds that lead to acidification of surface water. The response of forests to deposition of airborne acid and other air pollutants may be dependent on the same ecosystem processes.

Experimental Forests

University and government scientists are conducting long-term research on forest ecology and management at various experimental forests in all major forest types. Most of these forests are managed by the USFS, other federal and state agencies, and universities. The possibility that these forests may become sites for FRP sponsored research will be evaluated.

Forest Pest Management

Forest Pest Management (FPM), a staff unit within USDA Forest Service provides national technical support directly to federal forest resource managers and to state agencies and private forest managers through cooperative programs and projects. Major activities include forest insect and disease detection, evaluation, prevention, and suppression.

The Methods Application Group (MAG), located in Fort Collins, Colorado, is a detached FPM Washington office unit which provides specialized technical assistance nationwide, particularly in the application of new and improved technology for evaluating and reporting pest impacts. Activities include survey design, data analysis, serial photographic surveys, and data management with geographic information system technology.

Tennessee Valley Authority

The Tennessee Valley Authority is engaged in various projects on the deposition and effects of airborne acids and other pollutants within the Tennessee Valley. The purpose of this research is to assess the extent and magnitude of any damage, provide both an understanding of the processes responsible for such action and a basis for mitigative action, and develop baseline data for evaluating the effectiveness of mitigation and control measures.

National Science Foundation

The Long-Term Ecological Research Program of NSF supports ecosystem research at several sites in the U.S. A baseline or core-measurements component of the program requires routine measurements of key environmental and biological parameters. All sites have experiments in progress designed to examine ecosystem level processes which will contribute to our understanding of the effects of various atmospheric pollutants on ecosystem functions.

2.0 SCIENTIFIC FOUNDATIONS OF THE FOREST RESPONSE PROGRAM

2.1 Introduction

The most pressing issues currently facing decision-makers have to do with sulfur emissions. Therefore, top research priority has been assigned to questions involving the potential role of sulfur compounds in forest decline. Other pollutants, in order of policy priority, are nitrogen compounds, H^+, metals, O_3, H_2O_2, and hydrocarbons. However, because atmospheric pollutants occur in combination and interactions may be critical, studying combinations of pollutants is encouraged by the FRP.

Forest Response Program strategy was devised to answer the three policy questions as rapidly and as efficiently as possible. There are several aspects to this strategy.

The FRP will utilize two major conceptual approaches to the study of the effects of atmospheric deposition to forests: (1) epidemiological; and (2) physiological/ecological. The epidemiological approach is characterized by broad surveys of forest condition and a search for spatial or temporal patterns that may be related to other environmental patterns, including patterns of atmospheric deposition. Analyses of historical data will also be an important activity in this approach.

The physiological/ecological approach is characterized by more focused studies on the effects of particular environmental states on the health of individual trees or stands. Studies include controlled manipulative laboratory, greenhouse, and field experiments with combinations of pollutants and intensive field classification studies.

Epidemiology will be used to address P.Q. 1, which identifies forest resources that may be affected by atmospheric deposition, while physiological and ecological studies will establish cause-effect relationships, quantify

responses where possible, and determine the time frame in which a mechanism is likely to operate (P.Q. 2). Time scales are particularly important from a regulatory perspective because some mechanisms that effect tree growth may operate very quickly (i.e., hours for certain gases) while others may require years to take effect (i.e., certain soils processes).

Results from addressing P.Q. 1 and P.Q. 2 will be needed to estimate regional forest response to atmospheric deposition (P.Q. 3). The estimation of regional results will be achieved through models of physiological and ecological processes and forest dynamics.

To address the policy questions, each has been translated into a set of scientific questions. The information needed to answer each scientific question will be provided through the completion of a sequence of discrete research tasks which will be addressed in a logical progression. The task sequences also ensure that different Research Cooperatives will use similar protocols to address similar questions.

Within each task sequence one research task has been designated as critical. A critical task is the first whose outcome can be used to reject an hypothesis. If it is not rejected, further research is warranted and a subsequent critical task will be identified. Decision criteria have been developed for evaluating the outcome at each of these decision points. A decision criterion is an objectively defined statement that allows the FRP to give a definitive answer to a particular research task and scientific question. For each decision criterion, the FRP will define a Data Quality Objective or DQO. The DQOs, outlined in a separate DQO document, provide quantitative guidance to scientists through estimates of biological significance, the level of statistical significance, and power required to evaluate the hypotheses (Appendix B). The DQOs are useful as a management tool for ensuring accurate decisions

leading to efficient allocation of resources. The critical task approach means that many of the task sequences outlined here may not need to be carried to completion to answer the scientific question.

Scientific questions derived from P.Q. 2 take the form of specifically hypothesized mechanisms of how atmospheric pollutants may affect forests. The hypothesized mechanisms were derived from analysis of past data and scientific exchange within and between U.S. and European scientists. The hypotheses are described briefly in this section and are covered in greater detail in the Cooperative research plans. However, flexibility is stressed by the FRP. As the Program evolves, new relevant hypotheses can be developed and original hypotheses adapted. The FRP recognizes that more than one mechanism may be acting simultaneously. Hypotheses are not mutually exclusive or all inclusive.

Whenever possible, scientific questions will be addressed with existing data and, where a strong scientific consensus is reached, no additional research will be conducted to reject a mechanism. Research projects will be developed around specifically hypothesized mechanisms where data are insufficient to accept or reject them.

The three policy questions, with their associated scientific questions, will be addressed simultaneously. One important advantage of this approach is that survey/review results may provide information on the appropriateness of some of the hypothesized mechanisms, while mechanistic study results may indicate the potential of certain regions and forest types to be affected by atmospheric deposition. Likewise, controlled experimental studies may identify parameters or "bioindicators" of forest response to pollutants that would be useful in field surveys.

Simultaneous model development and data collection from P.Q. 1 and P.Q. 2 are desirable for several reasons. First, this approach encourages feedback

between model developers and researchers as their activities progress. Models should evolve to reflect only relevant mechanisms and interactions, many of which will be identified by controlled studies. In addition, the analytical framework of modeling will be available so that new research can be designed to produce the data necessary for model development and application.

The first step in addressing the policy questions with scientific questions is to settle on the primary variable of interest. In describing the policy questions, we have used the terms forest damage and forest resource,* each of which has different implications. We have settled on the use of the term "condition". While this is not a precise term, it represents our choice of the primary variable in a particular scientific question. One important point to remember about any particular choice of response variable is that forest "condition" is always a function of the time when it is measured.

The second step is to decide how to represent the primary object of interest, i.e., the object whose "condition" is being measured. There are several potential choices, including: tree, stand, and forest. There is no single good choice for a term to represent the object of interest at a general level. The different policy questions ask for information on all of these levels. However, the non-linear interactions of tree biology force us to consider the stand as the primary object of interest. Physiological and mechanistic research at the tree level will be needed to help us understand stand level responses.

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* While tree growth is a major emphasis of this program, it is understood that the forest ecosystem includes other organisms, including wildlife. The use of the wood "forests" throughout this plan includes other aspects of the ecosystem.

2.2 Translation of P.Q. 1 Into Scientific Questions

The initial scientific translation of P.Q. 1 is: Are there forest stands in North America whose condition departs significantly from those trend expected by the action of natural agents?

The conditions of primary interest at this time are reductions in growth rate of stands or large numbers of individual trees, the presence of unusual foliar symptoms, and unexplained increases in mortality. These conditions cover the reported phenomena for red spruce, the several species of southern pines, the reported decline of sugar maple in Canada, northern New England, and New York, and eastern white pine. More may be added if there is justification from reported data in the field.

Because stand condition is explicitly a function of time, we must determine whether or not a trend exists. In most cases this will have to be estimated, perhaps by projection. Actual condition will also often have to be estimated from incomplete data. We are primarily interested in detecting recent changes in the trend of forest condition at a variety of localities. If historical data are lacking, we may be forced to use the standard ecological approach of substituting space for time to achieve some ability to detect departures from expectation. In any case, we must know the natural bounds of variation in forest condition as a prerequisite for any analysis of the presumed association of pollution with changes in condition.

Since both baseline information and current measurements involve estimations, we must characterize the difference between the two as a departure of observed from expected, with associated confidence limits. A schematic comparison showing divergence from expected growth with non-specified confidence intervals is illustrated in Figure 2.

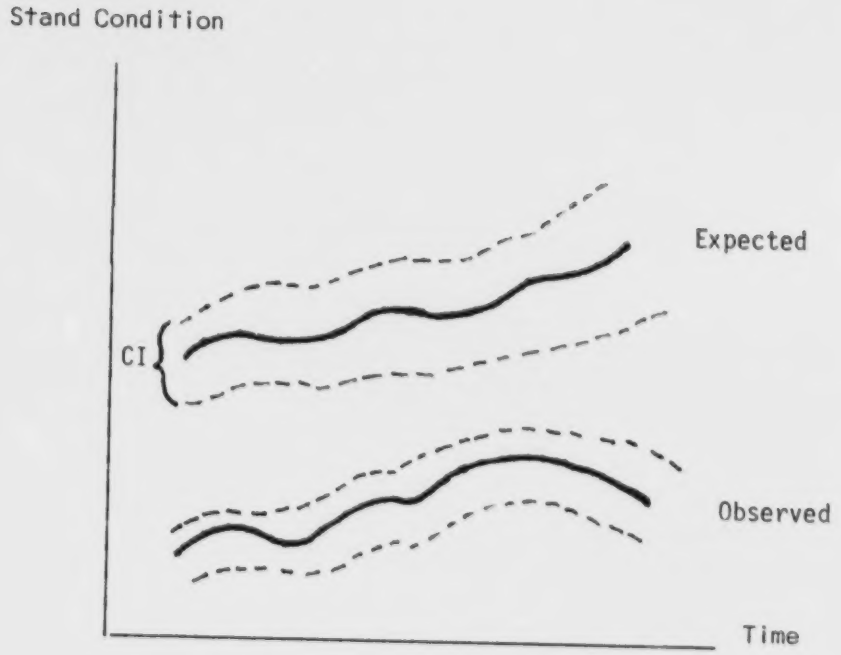

Figure 2. Measuring trends of conditions (with confidence intervals -- CI) where response is the departure of observed trend from expected trend.

Our estimate of expected condition must account for known natural factors and non-deposition human factors (e.g., logging) as much as possible. The difference between actual and expected condition is then the response of the stand to air pollution. Our initial scientific question can thus be divided into two questions:

1.1*: Are changes in condition greater than can be attributed to typical trends and levels of natural variability?

1.2: What spatial patterns exist in forest condition and how do these patterns relate to spatial patterns of pollutant exposure?

S.Q. 1.1 Temporal Patterns -- Research Tasks

Task 1. Complete a set of temporal case histories for stand condition. Stand condition might include radial increment, basal area increment, incidence of mortality, incidence of foliar pathology, stand composition, or changes in reproduction.

Sub-task 1. Document both the trend and the variability of the condition. In some instances historical data could include landscape changes over time from photographs. Likewise there could be situations which might give information on temporal variability, such as sites where a mill was built and subsequently removed. Probable sources of historical data include:

a. FIA (Forest Inventory Analyses)

b. USFS fixed plot remeasurement data

c. University research forests

d. Special studies

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* Scientific questions in this document are numbered according to the following convention: the numbers to the left of the decimal refer to the pertinent Policy Question, and the numbers to the right of the decimal are sequential.

e. FRP intensive sites

f. Cooperative research with industry

g. Remote sensing data bases

Sub-task 2. To complement the historical data, obtain matching current data, especially from forest stands where the effect of air pollution is plausible. Some balance of the likelihood of damage and the quality of the information should be sought as a secondary criterion.

Sub-task 3. Statistically analyze both historical and current data for trend and variability, with confidence intervals.

Task 2. Analyze recent changes in forest condition which could be attributed to pollution. That is, test for significant departure of current forest condition from the trend of expected (non-pollution) condition, recalling that forest condition is always a function of time,

a. Use "time series" techniques (Box-Jenkins, Econometric Regression, etc.);

b. Covary condition with appropriate non-pollution variables; and

c. Provide confidence intervals for estimates.

S.Q. 1.2 Spatial Patterns -- Research Tasks

Task 1. Find presumptive current severe gradients. That is, specifically focus on cases presumed to be precipitous gradients away from hot spots, i.e., high deposition or severe forest damage. The gradient of pollution must be relatively well-specified, and will not necessarily be geographically linear. The responses of condition (e.g., growth changes) to pollution must be arrayed using spatially statistical methods.

Task 2. Do a pilot study, appropriately stratified to estimate condition variability (within forest stands on the gradient) and estimate spatial interpolation power.

Task 3. Do a complete study, using the pilot study to determine the sampling proportion (the ratio of the number of sites to number of replicates).

Task 4. Test patterns of forest condition for significant geographic variation. This must be done using spatial statistical methods, appropriate non-pollution covariates, and must include confidence intervals.

Various gradients may be considered suitable for study, primarily on the basis of presumptive severity of effect, and secondarily on the balance of condition/deposition severity and potential quality of information.

S.Q. 1.1 and 1.2 -- Decision Criteria

We will conclude that there are forest stands in North America whose condition departs significantly from the trend expected by the action of natural agents if one of the following provisions is satisfied:

1. The variation in condition falls clearly outside the range of natural variability of these phenomena.

or

2. If the variation in conditions is inside the range of documented variability and there is a significant spatial association with acidic deposition alone or in combination with other pollutants.

2.3 Translation of P.Q. 2 Into Scientific Questions

Addressing this policy question is the most experimentally based activity within the Forest Response Program. We have translated it into scientific

questions by rephrasing the general question into several questions that are more specific with respect to the pollutant that is suspected and the hypothesized mechanism of action. Thus, each scientific question takes the form:

What is the effect of pollutant(s) x on forest y through mechanism z?

We have proceeded by: (1) developing an overall scientific rationale and framework; (2) developing the particular research task sequences needed to experimentally address each scientific question; and (3) identifying within each sequence a critical task and accompanying decision criterion that states the conditions under which we can reject the hypothesized mechanism. There is obviously some pre-selection of those mechanisms that are included in this analysis. We have included the most plausible hypotheses that have appeared in international scientific publications and those that have been defined in recent planning meetings and workshops. Detailed reviews of the pertinent scientific literature are contained in each Research Cooperative Plan. Several hypotheses, however, have no substantial direct field evidence to support them at this time; they are based primarily on laboratory and greenhouse studies or minimal observations in the field. The following discussion briefly summarizes the hypothesized mechanism underlying each scientific question.

Soil acidification, or reduction in percent base saturation, is a natural process occurring in most soils in humid regions. Atmospheric deposition of acidic and acidifying substances may have accelerated the rate of soil acidification beyond that due to natural acidification processes.

Soil Mediated Mechanisms

In many soils, aluminum is normally present in an insoluble non-toxic form. Increased solution acidity may lead to increased weathering of clay minerals and thus increased concentrations of soluble Al^{3+} in the soil. Heavy

metals, especially lead, have been deposited on some forests where they accumulate in the litter and upper soil layer (Friedland et al., 1984; Jackson et al., 1978). As with aluminum, increased solution acidity can cause increased concentrations of soluble metal ions in soil water. It is known that high concentrations of soluble metals are toxic to roots and mycorrhizae (Abrahamsen and Tveite, 1983; Foy, 1974; Schier, 1985; Ulrich, 1980; Wong, 1982) and can cause reduced growth (Shafer et. al., 1985) and reduced photosynthesis (Rolf and Bazzaz, 1975). Laboratory studies have demonstrated altered microbial activity resulting from increasing metal mobility with decreasing solution pH (Babich and Stotsky, 1979; Clark and Clark, 1981; Ruhling and Taylor, 1973; Tyler, 1975). What remains unknown is whether acidic deposition sufficiently increases acidification of the soil solution beyond the natural acidification process to mobilize those toxic concentrations. Soil microbial populations are indispensable mediators of nutrient cycles because of their role in decomposition and mineralization. Significant disruption of these populations would alter normal nutrient cycling and decrease nutrient availability to plants.

Although nitrogen plays a key role in maintaining the vigor of ectomycorrhizae, excess nitrogen may be harmful. Nitrogen toxicity can occur in the absence of acidification; it is the nitrogen itself that is of primary concern. The links between nitrogen deposition and mycorrhizal and plant response under field conditions, however, have not been made.

Leaching of nutrient cations occurs as H^+ ions in the soil solution exchange with basic cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, etc.) adsorbed to soil particles. Once in solution, the cations, along with mobile anions, are leached from the soil profile. Nutrient cation leaching has been demonstrated experimentally under both laboratory and field conditions (Abrahamsen, 1980a,

b, c; Bjor and Teigen, 1980; Haman, 1977; Huete and McColl, 1984; Lee and Weber, 1982; Schier, 1984; Stuanes, 1980).

The applicability of this hypothesis to forest decline is dependent on demonstrating that acidic deposition increases the rate of soil acidification and that the increased rate of acidification and concomitant loss of nutrients has a negative effect on tree growth through a net increase in leaching. The major limitation to interpreting the role of cation leaching is that cation replacement (e.g., weathering) and recycling processes are not well understood. Weathering of minerals within the soil profile continually resupplies nutrients to exchange sites. Trees continually cycle and redistribute nutrients between soils and biomass. Atmospheric inputs of dry and wet deposition add base cations in addition to acidic cations and anions. The relationship between acidic deposition and these processes is not well known, even for intensively studied sites, and regional differences in the importance of these processes have not been quantified.

Nutrient Leaching From Foliage

Foliar leaching is also common in humid ecosystems and has been well documented (D. Johnson et al., 1982; Likens et al., 1977; Tukey, 1970). Leaching is a normal part of nutrient cycling and does not adversely affect the plant as long as the critical internal nutrient balance is maintained by plant uptake. Increased H^+ loading by atmospheric deposition, however, may act to accelerate normal leaching rates. Several studies have demonstrated a correlation between precipitation pH and base cation removal (Hoffman et al., 1980; Scherbatskoy and Klein, 1983; Wood and Bormann, 1975). This hypothesized leaching response is also related to ozone toxicity in that leaching is increased after ozone causes injury to cell membranes (Prinz et al., 1982). A

major unanswered question is whether an increased loss of cations from foliage results in a net nutrient imbalance and subsequent physiological impairment.

Altered Physiology and Carbon Allocation

Changes in allometric growth or internal photosynthate allocation can result in increased water or nutrient stress. Nitrogen inputs, for example, promote relatively more growth above ground than below ground and may ultimately lead to increased susceptibility to drought (Kramer and Kozlowski, 1979). More generally, however, any stress that reduces photosynthetic capacity below the level required for growth and development of above ground tissues will result in reduced carbohydrate allocation to root systems (McLaughlin and Shriner, 1980). Ozone and other gaseous air pollutants have been demonstrated to interfere with photosynthate translocation to roots (McLaughlin and McConathy, 1983) and between growing and mature foliage.

Winter Injury

Plants protect themselves from winter freezing through a cold hardening process involving metabolic changes that take place annually after the period of active growth. Nitrogen inputs may prolong active growth, delay cold hardening, and increase the risk of freezing in late autumn or early winter (Kramer and Kozlowski, 1979; Soikkeli and Karenlampi, 1984; Tisdale and Nelson, 1975; Westman and Fournier, 1984). Desiccation is another stress that can cause winter injury. Internal water status is particularly crucial in winter when soil water may be frozen and therefore unavailable to plants. Air pollutants may erode or retard the development of the leaf cuticle that restricts water loss (Fowler et al., 1980; Huttunen and Laine, 1983; Shriner, 1983). It has also been suggested that fertilization by atmospheric nitrogen may promote

a break in dormancy during mid-winter periods that result in subsequent freezing damage. Friedland et al. (1984b) observed visible foliage damage on red spruce in Vermont that appeared to be caused by cold stress or winter desiccation.

Disruption of Reproduction or Regeneration

Reproduction and regeneration are fundamental processes of forest succession. Reduced pollen, seed, or seedling viability would have an important impact on community dynamics and successional patterns. Relatively little research has been done on the effects of air pollutants on the reproduction and regeneration of forest species and no specific physiological mechanisms are proposed here.

Altered Susceptibility to Pests and Pathogens

Pests and pathogens are normal components of forest ecosystems that trees are adapted to resist. Trees that are weakened from any kind of biotic or abiotic stress, however, may become more susceptible to attack by pests and pathogens. Air pollution induced stress is known to produce physiological changes and loss of vigor that are sometimes accompanied by pest and pathogen attack.

Scientific Questions 2.1-2.6

The following scientific questions have been identified to provide information to address Policy Question 2. They are based on our current knowledge and are by no means a permanent, fixed set.

2.1 What is the effect of sulfur and/or nitrogen pollutants on forests through the mechanisms of:

(1) Direct toxicity to roots, mycorrhizae, or soil microbial populations by mobilized metals in acidified soil water;

(2) Nitrogen toxicity to mycorrhizae;

(3) Increased leaching of soil nutrients resulting in reduced nutrient availability.

2.2 What is the effect of sulfur and/or nitrogen derived pollutants alone or in combination with oxidants on forests by the mechanism of increased leaching of foliar nutrients?

2.3 What is the effect of sulfur and/or nitrogen pollutants, alone or in combination with oxidants, on forests by the mechanism of altering photosynthesis, respiration, and carbon allocation patterns (e.g., morphology) with possible induction of water and/or nutrient stress?

2.4 What is the effect of nitrogen compounds, possibly in combination with oxidants, on forests through the mechanism of delayed cold hardening or early break in dormancy resulting in increased winter damage?

2.5 What is the effect of sulfur and/or nitrogen pollutants, alone or in combination with oxidants, on forests through the mechanism of disrupting reproduction or regeneration?

2.6 What is the effect of sulfur and/or nitrogen pollutants, alone or in combination with oxidants, on forests through the mechanism of altered susceptibility to pests and pathogens?

As shown in Figure 3, all task sequences begin by characterizing pollutant deposition. All sequences end by estimating the effects of atmospheric deposition in terms of growth, mortality, or symptomatology. In addition to characterizing deposition, a number of other research tasks are common to several sequences. In the following discussion, we will describe each task the first

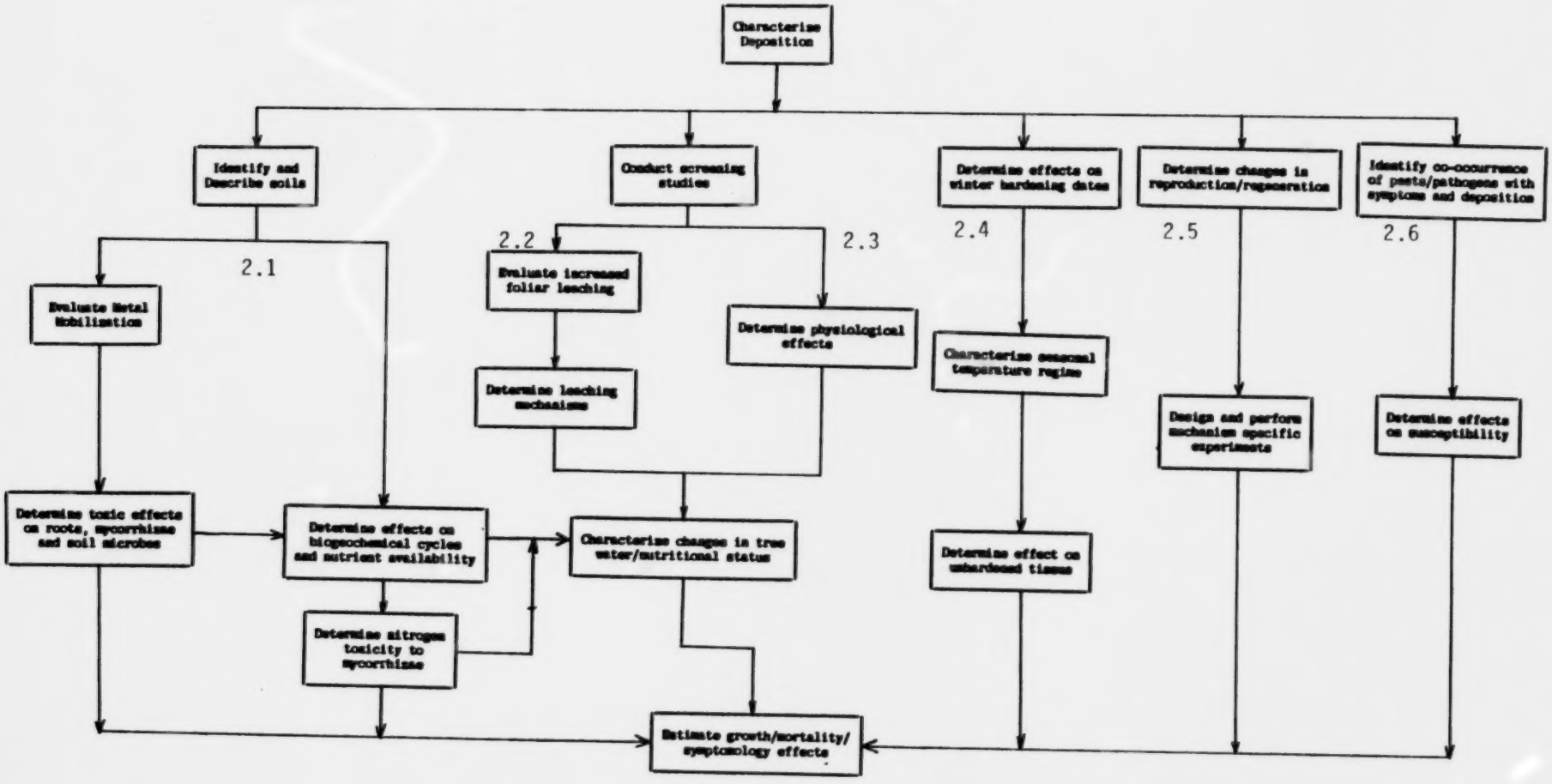

Figure 3. Overall scientific framework and chains of inference for Policy Question 2.

time it is referenced, but thereafter we will only list it by name. We recognize that there may be alternatives to each of the pathways presented here. Based on the current knowledge of program and extramural scientists and initial review, however, these sequences were selected as the most appropriate approaches.

All of the following sections use experimentation to uncover cause and effect relationships. Experimentation, however, should not be thought of as something that takes place only in the confines of the laboratory, greenhouse, or exposure chambers. This is especially true in the context of the Forest Response Program. Successful completion of the program's objective will ultimately require the demonstration that the hypothesized mechanisms operate in the forest under field conditions using common environmental conditions and realistic pollutant doses. This can only be accomplished by experimental manipulations in the field. As noted earlier, the task descriptions that follow are somewhat general so as to allow flexibility. Whenever possible, however, the completion of tasks should include field experiments.

Another valuable type of information that can help to answer the scientific questions listed above can be derived from comparisons of sites that appear to be sustaining air pollution effects with other sites free from such effects. While this information will be correlative, rather than a strict indicator of cause and effect, it will be valuable for identifying the most plausible hypotheses, and for verification of experimental results. For example, if the concentration of toxic metals is higher in soil water from an affected site than from an unaffected site, the hypotheses based on metal toxicity will gain credibility. The results from site comparison studies will be integrated with results from manipulative experimental studies.

Site comparison studies should be closely coordinated with activities undertaken to address P.Q. 1. S.Q. 1.2 pertains to the relationship between spatial patterns of forest condition and spatial patterns of pollutant exposure. Gradients in forest condition that will be identified for these studies should also be used to compare other specific variables related to hypothesized causal mechanisms. The variables that should be investigated and the scientific questions to which they relate are shown in Table 2.

S.Q. 2.1 (Soil Mediated Mechanisms) -- Research Tasks

This scientific question deals with soil processes and includes several related mechanisms. Because they are related, we encourage integrated approaches to research.

Task 1. Characterize deposition.

The first step in any of the subsequent task sequences is to assemble all of the existing relevant deposition information and, for specific research questions, to acquire new deposition information. Relevancy is defined by the particular scientific question being addressed, the chemicals involved, their temporal and spatial patterns, and their physical form. We have used deposition in a very broad sense, meaning wet and dry forms, cloud moisture, and gases. We expect that each intensive research site will have complete deposition monitoring.

To ensure the relevance of deposition data, we propose four specifications:

1. Deposition variables. These variables should be described not only with respect to the particular question being asked, but also with respect to the methods of measurement. Standardized methods are

Table 2. Specific variables to be used in site comparisons and the scientific questions to which they relate.

Variable	Scientific Question	Hypothesized Mechanism
Soil soluble metal status	2.1	Toxicity to roots and mycorrhizae Toxicity to soil microbial populations
Soil nutrient status	2.1	Nitrogen toxicity to mycorrhizae Soil nutrient leaching
Tree nutritional status	2.1 2.2 2.3	Toxicity to soil microbial populations Soil nutrient leaching Foliar nutrient leaching Altered physiology and carbon allocation
Incidence of apparent winter injury	2.4	Winter injury from freezing or desiccation
Apparent regeneration success	2.5	Disruption of reproduction and regeneration
Incidence of pests and pathogens	2.6	Increased susceptibility to pests and pathogens

necessary in order to achieve strict comparability of data across research sites and even between experiments at the same research site. Standardized methods of measurement will also help achieve more efficient quality assurance/quality control and data management.

2. Compounds or mixture of compounds. Of special importance to the FRP are those hypotheses and mechanisms that deal with the potential effects of acids and acid precursors. The most important policy questions revolve around these compounds, but we should also encourage investigation of interactive effects with other pollutants.

3. Spatial scales. There are at least three relevant spatial scales of interest. First is information from monitoring stations on or near intensive research sites which make the task of interpolation (or extrapolation) to that site easier. Second is deposition information on a regional scale (over a forest type) which may involve more analysis of existing data than new data collection. Third is deposition information on an elevational basis. The spatial deposition data should be initially assembled in digitized format so maps can be produced that are relevant to particular potential mechanisms.

4. Temporal scales. For hypotheses that rely on indirect mechanisms of effect (e.g., soil leaching, metal mobilization, winter injury), the appropriate temporal scales of measureing deposition appear to be weekly to monthly. For hypotheses that rely on more direct mechanisms of effect (any hypothesis that has a component from oxidants or sulfur dioxide), the physiologically relevant time scales are closer to hourly and/or real-time measurements.

The product of this step will depend on the particular question being asked. For regional comparisons of nitrogen deposition it might be a series of maps of the monthly average wet deposition of nitrate, supplemented by calculations of the deposition of other nitrogen species and dry deposition. For a particular experiment, it might be a temporal sequence of episodes of SO_2 events or O_3 events.

Task 2. Identify and describe soils.

This task is common to all of the soil mediated mechanisms and research should be coordinated among them.

The specific soils to be studied must be identified and their pertinent characteristics described. We can begin by identifying the particular places where tree species of interest grow, and verifying the soil types that actually occur there. A first step in this is simply to overlay maps of soil types with forest types. A more complete treatment involves sampling on intensive research sites to verify the broader scale soil maps. In order to decide which of these is more important, we need to specify the spatial scale of the question that is being investigated.

We must then specify the physical and chemical properties of the soils and soil water with respect to soil type, nutrient status, and metal concentrations. This step is important because classical soil taxonomy may not reliably indicate a particular soil's probable response to acidic deposition in the field.

Task 3a. Evaluate increased mobility of toxic metals by both manipulative experiments and field sampling along gradients of apparent forest decline or air quality.

Task 3b. Determine effects of acidic deposition on biogeochemical cycles and nutrient availability.

This task is also common to all of the soil mediated mechanisms. Experimental results should be used to contruct models of biogeochemical cycles or to modify existing models. This is an excellent oppportunity to integrate research with other NAPAP programs, particularly the Direct/Delayed Response and Watershed Manipulation Projects, as well as EPRI projects. An important use of these models will be to develop projections of the status of soil nutrients and metals with respect to acidic loading.

This task should include demonstrating increased nutrient leaching by manipulative experiments and field sampling along gradients of apparent forest decline or air quality. Field sampling studies should compare current soil nutrient status along these gradients.

It is important to think in terms of nutrient cycles rather than simply leaching losses, and to distinguish between available and total nutrients. Some leaching losses may be offset by weathering or decomposition, although the relative rates of these interacting processes are critical. Relatively small amounts of some nutrients may be in forms available for plant uptake. If available nutrients are lost and not replaced, uptake may be limited even though total nutrient pools remain high.

Toxic effects on soil microbes are of interest primarily because of possible implications for soil and tree nutrient status. Through laboratory and field experiments, and modeling exercises, this task also seeks to quantify any change in nutrient cycles caused by disruptions of microbial populations and the processes that they mediate.

Clearly, a variety of methods could be used to conduct these experiments. Laboratory experiments, conducted under controlled conditions, are one obvious

possibility. Ultimately, however, we must demonstrate that these processes occur in nature. This will require experiments in the field.

* Tasks 3a and 3b are the critical tasks in this sequence; if significant mobilization of metals, increased levels of soil nitrogen, or increased leaching of soil nutrients do not occur, we will reject these mechanisms.

Task 4a. Determine toxic effects of metals on roots, mycorrhizae, and soil microbial populations.

Results from Task 3 should be used to design experiments that will test for toxic effects on roots, mycorrhizae, and soil microbes. The question to be addressed is: Are the concentrations and speciation of metals mobilized in soil solution by near ambient levels of acidic deposition (or snowmelt) toxic to tree roots, associated mycorrhizae, or soil microbes? Here again laboratory experiments will be an important tool, but results in the laboratory must be verified and demonstrated in the field.

Task 4b. Determine toxic effects of nitrogen on mycorrhizae.

Task 5. Characterize changes in tree nutritional status.

If nutrient availability or uptake are seriously affected, it will eventually be reflected in tree nutritional status. To accomplish this task we must establish a method to summarize trees' current nutritional status relative to their requirements.

Task 6. Estimate growth/mortality/symptomatology effects.

This task is common to all task sequences. The result should be quantitative and should be very closely coordinated with modeling activities related to

Policy Questions 3. Estimates of effects under this task will form a critical source of information for determining forest-level dose/response relationships.

S.Q. 2.2 Foliar Leaching -- Research Tasks

Task 1. Characterize deposition.

Task 2. Conduct controlled exposure screening studies to identify changes in plant condition.

This task is common to two of the hypotheses related to direct effects on tree physiology (i.e., effects not directly mediated by soil processes). The rationale behind this task is that if pollutant exposure does not have an effect on tree growth, mortality, or symptomatology, then there is little reason to investigate more specific mechanisms of potential injury.

Task 3. Evaluate increased foliar nutrient leaching by both manipulative experiments and field sampling along gradients of apparent forest decline or air quality.

* This is the critical task in this sequence; if exposure to air pollutants does not result in a significant increase in foliar leaching, we can reject this mechanism.

Task 4. Determine mechanisms of increased foliar leaching, e.g., mechanism of increased membrane permeability; concentration gradients -- transport of ions to needle surface, etc.

Task 5. Characterize net changes in tree nutritional status.

Task 6. Estimate growth/mortality/symptomology effects.

S.Q. 2.3 Plant Growth Processes -- Research Tasks

Task 1. Characterize deposition.

Task 2. Conduct controlled exposure screening studies to identify changes in plant condition.

Task 3. Determine the effects on physiological processes.

Growth is the net result of various processes involving the uptake and efficient utilization of carbon (energy), water, and mineral nutrients. The operational question here is: How are the physiological processes of photosynthesis, respiration, and carbon utilization altered when plants are exposed to sulfur, nitrogen, or oxidant pollutants?

* This is the critical task in the sequence; if exposure to air pollutants does not result in a significant change in physiological processes (and morphology), we can reject this mechanism.

Task 4. Characterize changes in tree nutritional and water status.

Alterations in physiological processes can result in general growth reductions or in changing patterns of carbon allocation leading to morphological change. Morphological changes may increase water and nutrient stress by altering the ratio of belowground to aboveground tissues.

Task 5. Estimate growth/mortality/symptomatology effects.

S.Q. 2.4 Winter Damage -- Research Tasks

Task 1. Characterize deposition.

Because this scientific question relates to plant phenology, it is particularly important to consider seasonal deposition patterns here. Timing may be a critical variable.

Task 2. Determine effects on winter hardening dates.

This task addresses the heart of this hypothesis. Will near ambient amounts of nitrogen (and possibly oxidants), deposited at a particular time of the year, prolong the period of active growth and delay the winter hardening process or promote an early break in dormancy to the point that the plant will be susceptible to damage from low winter temperatures?

Both manipulative experiments and field sampling should be used to quantify changes in processes such as starch to sugar conversion and cuticular wax formation rates due to excess nitrogen and oxidants.

* This is the critical task in this sequence; if growth is not extended and winter hardening processes are not significantly delayed, or if a significantly early break in dormancy does not occur, we can reject this mechanism.

Task 3. Characterize a seasonal temperature regime representative of field conditions.

As hypothesized here, winter injury would occur as a result of the interplay between acquisition or loss of hardening and the occurrence of cold temperatures. We need to carefully consider previously observed winter temperatures at high elevations throughout the range of red spruce.

Task 4. Determine the effect of typical temperature regimes on unhardened tissue through foliar freezing and desiccation injury.

The result of this task should be an identification of the consequences of the interactions of different degrees of hardening and different temperatures.

Task 5. Estimate growth/mortality/symptomology effects.

S.Q. 2.5 Reproduction -- Research Tasks

Task 1. Characterize deposition.

Task 2. Determine if reproduction and/or regeneration are showing a change that can be plausibly attributed to deposition.

Subtask 1. Identify field situations for which changes in reproduction and regeneration can be plausibly attributed to deposition.

* This is the critical task in this sequence; if such situations cannot be identified, we can reject this mechanism.

Subtask 2. Assemble known laboratory evidence indicating a plausible effect and suggesting more specific hypotheses of mechanism.

Task 3. Design and conduct specific experiments combining mechanisms suggested by Subtask 2 and situations found in Subtask 1.

Task 4. Estimate effects on community dynamics and successional patterns, as well as growth/mortality/symptomology effects.

S.Q. 2.6 Pests and Pathogens -- Research Tasks

Task 1. Characterize deposition.

Task 2. Identify key pests and pathogens and their co-occurrence in the field with trees showing decline symptomology and gradients of atmospheric deposition.

Literature sources and existing data should be used whenever available. Field surveys may be necessary to document co-occurrence.

* This is the critical task in this sequence; if there is no co-occurrence of pests and pathogens, decline symptomology, and atmospheric depositsion, we can reject this mechanism.

Task 3. Determine the effect of air pollutants on altered susceptibility.

This task should employ experimental manipulation and standard epidemiological approaches.

Task 4. Estimate growth/mortality/symptomology effects.

S.Q. 2.1 Through 2.6 -- Decision Criteria

In the preceding sections we identified critical tasks in each sequence that are decision points where hypothesized mechanisms can either be rejected or targeted for additional study. Decision criteria form the basis for rejection or continued work. Each decision criterion relates specifically to the kind of information that will be derived from the critical tasks. More specific definitions have been formulated by each cooperative and are discussed in their respective plans. The FRP will also consider alternative decision criteria that can be demonstrated to be equally valid.

S.Q. 2.1

We will conclude that the mechanism of direct metal toxicity to roots, mycorrhizae, or soil microbial populations is plausible and warrants further research if a representative sample of soils associated with a relevant forest type shows increased mobility of metals when exposed to a spatially representative sample of ambient and greatly above ambient sulfur and nitrogen derived pollutants in realistic temporal sequence under representative environmental conditions.

We will conclude that the mechanism of nitrogen toxicity to mycorrhizae is plausible and warrants further research if a representative sample of soils associated with a relevant forest type experience increased nitrogen concentra-

tion when exposed to a spatially representative sample of ambient or greatly above ambient nitrogen compounds in realistic temporal sequence under representative environmental conditions.

We will conclude that the mechanism of leaching of nutrients from the rooting zone is plausible and warrants further research if a representative sample of soils associated with a relevant forest type experience net increased nutrient leaching when exposed to a spatially representative sample of ambient and greatly above ambient sulfur and nitrogen derived pollutants in realistic temporal sequence under representative environmental conditions.

S.Q. 2.2

We will conclude that the mechanism of foliar leaching is plausible and warrants further research if a representative sample of trees experience an increase in foliar leaching when exposed to a spatially representative sample of ambient and greatly above ambient sulfur and nitrogen pollutants alone or in combination with oxidants in a realistic temporal sequence under representative environmental conditions.

S.Q. 2.3

We will conclude that the mechanism of alteration of normal physiological processes and carbon allocation patterns is plausible and warrants further research if a representative sample of trees experience a change in physiological condition when exposed to a spatially representative sample of ambient and greatly above ambient concentrations of sulfur and/or nitrogen pollutants, alone or in combination with oxidants, in realistic temporal sequence under representative environmental conditions.

S.Q. 2.4

We will conclude that the mechanism of delayed winter hardening is plausible and warrants further research if a representative sample of trees experience delayed hardening when exposed to a spatially representative sample of ambient and greatly above ambient concentrations of nitrogen compounds and oxidants in realistic temporal sequence under representative environmental conditions.

S.Q. 2.5

We will conclude that the mechanism of disruption of reproduction or regeneration is plausible and warrants further research if a spatial pattern of changes in reproduction or regeneration can be associated with the spatial pattern of deposition of sulfur and/or nitrogen pollutants, alone or in combination with oxidants.

S.Q. 2.6

We will conclude that the mechanism of altered susceptibility to pests and pathogens is plasible and warrants further research if a spatial pattern of pest and pathogen occurrence can be associated with a spatial pattern of apparent decline symptomology and a spatial pattern of deposition of sulfur and/or nitrogen pollutants, alone or in combination with oxidants.

2.4 Translation of P.Q. 3 Into Research Tasks

The answer to P.Q. 3 will come from a quantitative understanding of the dynamics of the response of forest condition to changes in pollution. That understanding will form the basis for the ability to predict change in forest condition in response to specific levels of pollution. The mechanism for

achieving a quantitative understanding of the dynamics of forests and for predicting future responses is the mathematical model. It is important to understand that there is no one best all-purpose model. Rather, different models will be developed depending upon the measure of condition used (growth, volume, symptomatology, etc.) and the object of interest (tree, stand, forest, region, etc.). Models will also differ in the kind of mathematical approach taken (deterministic, statistical, computer based, etc.). An important class of models will be individual tree based models of stand dynamics implemented on computers. Such models provide a mechanism for incorporating knowledge of the physiological processes of individual trees while acknowledging the non-linear interactions of individual trees which constitute stand dynamics. Many different models of this type may be needed for specific species or regions. Nonetheless, we can describe the general desired properties of any such predictive models:

1. It should be projectable in space and time for plantations as well as natural stands.
2. The projections, whether in spatial or temporal terms, should always be accompanied by confidence intervals and sensitivity analyses. Without such analyses, both scientists and decision makers will be unable to judge the confidence they have in the projections.
3. Models should be biologically interpretable so that causal mechanisms can be incorporated as they are identified from research related to the first and second policy questions. It is expected that the incorporation of new understanding of tree physiology and ecosystem dynamics will result in major advances in the science of forest growth and yield modeling.

4. The modeling effort should recognize the characteristics of forest resource data and air pollution data that will drive the model, and how they will evolve over time. Models will represent a synthesis of diverse information sources, especially with respect to forest and deposition inventories, and therefore models will need to be accessible to those information sources.

5. The needs of model users must be met by the modeling effort. This implies prior specification of required outputs, including their resolution, aggregation, response variables, and other factors, in addition to explicit statements of precision that are mentioned above.

6. Models should be amenable to evaluation, and a plan for model development should include model evaluation.

7. The modeling effort should use standard computer hardware and software where possible, and should not be overly expensive in application. Computing system requirements and typical cost structures should be made explicit.

8. Modeling efforts should provide for training of model users and for ongoing software maintenance and support.

Unlike the first two policy questions, not all of the above properties can be treated in a framework of translation into scientific questions (null hypothesis) and scientific tasks. The required products are models and procedures that are biologically and statistically sound and operationally useful. The process of model development itself will contribute to overall program success, as researchers and modelers interact to focus research on relevant questions, and as modelers synthesize new information. To the extent these

issues depend upon a logical and structured approach, they can be represented by a set of scientific questions and tasks.

The scientific question that will provide information to address Policy Question 3 is:

3.1 What is the dynamic response of forests to specified levels of acidic deposition, alone or in combination with other pollutants?

S.Q. 3.1 -- Research Tasks

The tasks necessary to implement this modeling effort fall into three groups: model planning and specification, model implementation, and model analysis and revision.

Model Planning and Specification. Any modeling effort must begin with the definition of the boundaries of the system to be modeled, the required statistical properties, and the desired output. Model users and their needs must be identified. Models are useful only to the extent that they satisfy the needs of model users, yet model users must be realistic in specifying their requirements.

Task 1. Critically review and classify existing models using a model taxonomy that might include:

a. position on "first principles -- pure data" continuum;

b. filter characteristics of the model;

c. filter characteristics of the calibration data;

d. statistical properties -- precision, accuracy, bias;

e. dynamic structure properties -- sensitivity;

f. accessability to forest and deposition inventory and other model-driving or -initiating data bases.

Task 2. Develop general guidelines for modeling and software engineering.

Such guidelines will apply to modification of existing models and/or development of new models, and should ensure that models are structured so as to allow modification for new data, new mechanisms, new species, etc.

Task 3. Work with decision-makers, other program scientists, and modeling specialists to define system boundaries, statistical requirements, and desired formats. We must create a picture of the general modeling task and expected outcome, and describe the tradeoffs that need to be made in the modeling effort.

The three-way tradeoff of generality, realism, and precision must be understood and evaluated by decision-makers. Two-way feedback of information between the activities under the first two policy questions and P.Q. 3 is essential. Synthesis and integration will serve as a focal point for this activity.

This two-way feedback will be an iterative task that will result in specification of model characteristics for a system that has a high probability of solution. Decisions that need to be made will include:

a. Physical criteria -- what are the indicators of interest to decision-makers?

b. Chemicals -- which air pollutants and/or combinations of air pollutants are of interest?

c. Forest types -- which forest types are of interest?

d. Management actions -- what types of resource and/or emission controls will be examined?

e. Statistical requirements -- accuracy, precision, and/or sensitivity?

f. Space and time -- what are the spatial and temporal resolution and aggregation levels?

g. Reporting formats -- how will the model be used?

h. Other considerations -- for example, cross-region compatibility, linkages with other task groups, deadlines for completion, etc.

Task 4. Identify and characterize ancillary data bases and models that will drive forest response models.

Examples include forest inventory data, deposition data and/or models, and soil or other ecosystem models.

Model Implementation

Task 5. Undertake the modeling for alternative distributions of exposure, including those assumed for alternative projections of acidic deposition, alone or in combination with other pollutants.

Model Analysis and Revision

Task 6. Describe the tradeoffs made during the course of developing these models.

These tradeoffs include the three-way tradeoff between generality, reality, and precision. They also include the cost of running the model to achieve particular results.

Task 7. Perform sensitivity analyses to identify critical assumptions and model components.

Task 8. Perform "Monte Carlo" or other analyses to determine the precision of the models.

Task 9. Perform validation analyses to determine the accuracy of the model.

Task 10. Provide for training of model users.

Task 11. Provide for continuation of software development and/or support at such time that personnel involved with preparing models for Policy Question 3 are released to other duties.

S.Q. 3.1 -- Decision Criteria

Models are tools to be used which do contain hypotheses, but are not accepted or rejected in the same way that hypotheses are. Nonetheless, like any tool, a model must be well made and useful for the job at hand. To achieve these properties, a model will be rejected or modified if:

-- It does not pass review by experts in modeling and computer science outside of traditional forestry science as well as within.

-- It is too insensitive to reasonable variation in exposure distribution.

-- Its statistical properties are not within the boundaries set during the planning stage and determined to be necessary to provide a meaningful answer to Policy Question 3.

3.0 PROGRAM IMPLEMENTATION

The preceding section presents the scientific foundations of the Forest Response Program and describes what must be done to accomplish the program's objective. This section discusses how those activities will be carried out and who will be responsible for their completion. The technical components of the FRP include: National Vegetation Survey (NVS), Spruce-Fir Cooperative (SFC), Southern Commercial Forest Cooperative (SCFC), Western Conifers Cooperative (WCC), Eastern Hardwoods Cooperative (EHC), Atmospheric Exposure Cooperative (AEC), Synthesis and Integration (S&I), and Quality Assurance Staff (QA) (Figure 1). For each cooperative, research priorities are stated by the scientific question and the rationale for establishing the priorities is described. Each of the program components has its own detailed implementation plan (copies available from program managers, Appendix A).

The contribution of each cooperative to the scientific questions involves five research approaches: (1) historical analysis and intensive field characterization studies; (2) controlled field or laboratory studies; (3) controlled field studies; and (4) modeling.

Historical data analysis and intensive site characterization supply information for S.Q. 1.1 and 1.2. Both involve analysis of spatial and temporal variability of natural factors and potential pollutant responses to identify changes in forest condition that may be caused by atmospheric deposition. All relevant historical data bases will be analyzed, including historical stand data from experimental forests and Forest Service inventory data. Historical records provide the data for comparisons of forest condition with temporal and spatial trends in pollutant exposure, and other environmental factors.

Intensive site characterization studies provide additional data for temporal and spatial analysis. Tree and stand growth chronologies can be analyzed for both temporal and spatial variability, while many other characteristics, such as foliar health and root vigor, indicate spatial variability. To maximize the use of spatial analyses, sites are strategically placed along gradients of atmospheric deposition, e.g., at varying elevations and aspects.

Correlations between forest condition and atmopsheric deposition (as described for each site through monitoring or extrapolations by the Atmospheric Exposure Cooperative) will provide the basis for answering S.Q. 1.2. Models may help in this analysis and will be applied when appropriate.

Research to identify possible mechanisms of pollutant impact (S.Q. 2.1-2.6) will utilize all five research approaches. Analysis of past studies or documentations of air pollutant effects on forest trees may provide insight for determining the most plausible potential mechanisms. Intensive site research, on the other hand, provides current data on forest condition which may indicate which mechanisms are acting under forest conditions. Data on all response levels (including biochemical/physiological, morphological, stand, and ecosystem) will be analyzed for any implications of acting mechanisms.

Controlled field and laboratory studies have advantages over site characterization studies in that they can: (1) keep natural factors constant; (2) vary pollutant inputs; and (3) more easily enable measurements of responses, particularly physiological response. However, seedlings are typically used in these studies and so extrapolation from seedlings to mature trees must be made. Controlled field studies are conducted because they may include realistic environmental conditions. We recognize that the most relevant studies will be those that use realistic pollutant exposures, representative genotypes, appro-

priate numbers of trees/seedlings, realistic environmental conditions, and have adequate replication.

Controlled studies will indicate not only the important mechanisms, but also dose-response relationships between individual tree and s atmospheric pollutants. Models will be designed specifically to use results of controlled experiments to estimate dose-response. Cooperatives will develop and apply models in conjunction with S&I. Feedback between S&I and the cooperatives will ensure appropriate bases for estimates of dose-response on both the cooperative and program-wide level.

3.1 National Vegetation Survey

The highest priority for the NVS are S.Q.'s 1.1 and 1.2; the NVS has primary responsibility for answering these questions and will initiate the appropriate tasks described in Section 2.0. Of major importance are studies relating forest condition to spatial variation in atmospheric deposition. These gradient studies will utilize known or strongly suspected gradients of atmospheric deposition. Other factors affecting growth will be kept as uniform as possible.

Additional fundamental activities include: (1) developing techniques for inventorying and monitoring atmospheric pollutant effects on individual trees and stands; and (2) developing analytical tools to assess forest condition relative to atmospheric pollutant exposure. The NVS will provide support to the research cooperatives involved in epidemiological research associated with these questions.

The NVS will participate with the Southern Commercial and the Spruce-Fir Cooperatives in identifying data needs for tasks related to Policy Question 2. Site specific information will be the responsibility of the appropriate cooper-

ative with the National Vegetation Survey providing technical input and support. Research projects funded by the NVS are described in the NVS Research Plan.

3.2 Spruce-Fir Cooperative

The Spruce-Fir Cooperative (SFC) will address the questions of extent and mechanism of atmospheric pollutant effect (S.Q. 1.1, 1.2, and 2.1-2.6) characteristic of the spruce-fir ecosystems of the eastern U.S. The Cooperative has established the following priorities for addressing the scientific questions:

Priority 1: S.Q.'s 1.1, 1.2, 2.2, 2.3, and 2.4

Priority 2: S.Q.'s 2.1, and 2.5

Priority 3: S.Q.'s 2.6

Specific rationale for these priorities is as follows:

1. To help answer whether there is a significant problem of forest damage in North America (Policy Question 1), the SFC must determine the temporal and spatial consistencies in symptomatology, growth and decline of red spruce and fir in the east. The extent and magnitude of such damage will help define future mechanistic research and aid in developing cause and effect relationships.

   The foliage is the first point of contact between pollutants and the tree. Mechanisms of direct effect on foliage (S.Q. 2.2), therefore, may prove to be most vital. The effects of pollutants on physiological processes (S.Q. 2.3) may take place through a number of pathways. Winter damage has been observed consistently in high elevation red spruce (S.Q. 2.4).

2. Scientific Question 2.1 deals with more indirect pathways of soil mediated effects since the soil chemistry must be altered to have an effect. The

probability of occurrence is lower and the time frame for effect is longer than the S.Q.'s dealing with above ground changes. This also holds true for mechanisms relating to reproduction/vegetation (S.Q. 2.5).

3. Pollution levels must be reached so that plant changes will be affected to the degree necessary to make the plants more susceptible to insect or pathogen attack. Such a mechanism, though feasible, is not likely to occur.

These are the initial priorities assigned to the hypothesized mechanisms. Emphasis may change as research progresses; priorities will be reviewed periodically for their appropriateness.

The SFC uses all four research approaches in addressing the S.Q.'s listed above. Intensive site locations for the cooperative are shown in Figure 4. These locations were chosen because they represent areas where decline of the spruce-fir forests has been reported or, in the case of Howland, ME, a large economic resource exists.

Modeling of tree response to pollutant effects is being emphasized in the SFC. Individual projects closely coordinated by Cooperative management and with the overall guidance of S&I are underway.

3.3 Southern Commercial Forest Cooperative

Scientific Questions 1.1, 1.2, and 2.1 through 2.6 are being addressed by the Southern Commercial Forest Cooperative (SCFC). These questions relate to possible extent and mechanisms of atmospheric pollutant effects specifically in southern commercial forest ecosystems. To focus research efforts, the Cooperative, considering past data and current observations, has established these priorities:

* Spruce-Fir Cooperative
** Southern Commercial Forest Cooperative
● Primary Research Site
▲ Secondary Research Site
Howland Exp. Forest, ME *
Mt. Moosilauke, NH *
Whiteface Mt., NY *
Mt. Rogers, VA *
Duke Forest, NC **
Mt. Mitchell, NC *
Clingman's Dome, TN *
Clemson Forest, SC **
Tuskegee National Forest, AL **
Austin Cary Forest, FL **
Stephen F. Austin Exp. Forest, TX **

Figure 4. Location of intensive research sites for the Spruce-Fir and Southern Commercial Forest Cooperatives.

Priority 1: S.Q. 2.3

Priority 2: S.Q.'s 2.1 (nutrient leaching aspect), and 2.2

Priority 3: S.Q.'s 2.1 (direct N toxicity), 2.5, and 2.6

Priority 4: S.Q.'s 2.1 (metal mobilization), and 2.4

Specific rationale for these priorities is as follows:

1. Highest priority has been placed on questions about mechanisms having direct impact on tree physiological processes and subsequent growth. Ranking progresses downward to S.Q.'s relating to mechanisms having an indirect impact through soils and soil microorganisms.
2. Scientific Question 2.3 (carbon allocation) is placed as highest priority because oxidant effects have been observed on pines located in the southern U.S. and because research on crops has found phytotoxic levels of oxidants in the rural south.
3. Scientific Question 2.4 (winter injury) is lowest priority because this question was developed specifically for red spruce stands at high elevation and is of questionable relevance to the SCFC.

These are the initial priorities of hypothesized mechanisms; emphasis may change as research progresses. Priorities will be reviewed periodically for their appropriateness.

As with the SFC, the SCFC will use all five research approaches to address these S.Q.'s. Historical data are being used to address S.Q.'s 1.1 and 1.2 in conjunction with the NVS. This work is particularly important given the reports of radial growth reduction in certain regions of the South.

Intensive site characterization is underway at one primary site and four secondary sites have been chosen (Figure 4).

3.4 Western Conifers Cooperative

The Western Conifers Cooperative (WCC) will address the scientific questions as they relate to coniferous forests in the 11 western states. Based upon current knowledge of air pollution and forest health in the West, the Western Cooperative has set the following priorities for addressing the scientific questions:

Priority 1: S.Q. 1.1, 1.2

Priority 2: S.Q. 2.3

Priority 3: S.Q. 2.1, 2.2, 2.4, 2.5, 2.6

These priorities were established with the following rationale:

1. There is little information in the West on spatial patterns of deposition and forest condition. Air quality or precipitation monitoring data are limited for forested regions of the West, particularly for high elevations. Extrapolation from emissions data and urban monitoring data to forests requires further development of transport models. Information on forest condition, both on typical trends and on deviations with possible links to air pollution, is also limited. An improved overview of the situation is required before specific mechanistic hypotheses can be selected and addressed. Under present planning scenarios, the AEC and NVS will be providing only minimal support for addresssing these questions in the West compared to their support for eastern cooperatives. Thus, S.Q. 1.1 and 1.2 will receive the highest priority from the Western cooperative.
2. Second priority is given by the Cooperative to S.Q. 2.3 (carbon allocation). Little is known about the relative sensitivities of the major western conifers to direct exposure to acidic deposition and oxidants. Measurements of the growth response of conifer seedlings to simulated ambient pollution regimes will be used to determine which species (and

therefore which geographic areas) should receive greater attention. Intensive studies of the remaining scientific questions will not be undertaken until justified by the results of the work on S.Q. 1.1, 1.2, and 2.3.

3.5 Eastern Hardwood Cooperative

The EHC is addressing S.Q. 1.1, 1.2, and 2.3. Considering our knowledge of the condition of eastern hardwoods forest, the EHC has set the following priorities:

Priority 1: S.Q. 1.1, 1.2

Priority 2: S.Q. 2.3, 2.2, 2.4, 2.5, 2.6

Priority 3: S.Q. 2.1

The rationale for the priorities is as follows:

1. There are currently no reports of regional forest damage or decline that can reasonably be attributed to atmospheric pollutants. Determining if a problem exists is therefore of highest priority, hence the emphasis on S.Q.'s 1.1 and 1.2.
2. Little is known about the relative sensitivity of eastern hardwood species to pollutants. Part of problem definition is to better understand how pollutants may affect the physiology of key hardwood species.

The EHC is approaching these S.Q.'s in three ways:

1. A detailed problem analysis, in which the available data to assess the importance of other "natural" declines in determining variability in forest condition will be evaluated in comparison to the potential scope of atmospheric deposition related problems.
2. Controlled exposure studies designed to initially screen priority eastern hardwood species for relative sensitivity to acidic deposition, SO_2, NO_x,

ozone, and associated pollutants. Emphasis will be on exposure regimes and concentrations relevant to field exposure conditions across the eastern hardwood forest types.

3. Measurement of forest condition and response along a pollutant deposition gradient(s).

Vegetation responses to atmospheric deposition within the eastern hardwood forest, if measurable, will likely be subtle and therefore will require a high degree of precision to detect. Since it is generally not known which eastern hardwood ecosystem components or processes are most susceptible or responsive to the pollutants of primary concern (sulfate, nitrate, and oxidants), a suite of vegetation and process measures will be needed to assess a broad spectrum of responses.

3.6 Atmospheric Exposure Cooperative

The Atmospheric Exposure Cooperative was formed to support the FRP by: (1) characterizing deposition and air quality in forests of the U.S. on biologically relevant temporal and spatial scales; and (2) monitoring air quality and deposition at specific sites. Monitoring stations will be co-located with the intensive research sites of the Cooperatives so correlations of forest condition with atmospheric deposition can be made. Monitoring is an important contribution in efforts to characterize deposition to forests, since most existing air quality data are for urban areas.

Characterization of atmospheric deposition is necessary as a basis for developing realistic regimes to be used in controlled laboratory and field studies. Such information can also be used for evaluating the relevance of a variety of controlled exposure procedures. It is likely that the responses of trees and stands to pollutants are governed by a combination of the climatic

conditions and dose to which they are exposed. We need to know the meteorological and exposure parameters to develop biologically relevant conditions for controlled exposures.

The AEC will analyze existing air quality data from all available relevant sources. Sources include those of both the federal government, universities, and private research organizations. Monitoring, as stated, may be used to fill in gaps when needed and possible. Models of atmospheric dispersion and chemistry may be of considerable use in the estimation of forest exposure. For example, theoretical calculations may be used to interpolate between monitoring sites located some distance apart. Microscale processes which influence biological response may also be described using theoretical quantitative models. Models made available by this cooperative will also be of use in the other cooperatives and the Synthesis and Integration Staff.

3.7 Synthesis and Integration

The Synthesis and Integration Project (S&I) is responsible for producing program-wide technical outputs (see Table 4, Section 5) and for ensuring that the research conducted by the FRP contributes effectively and efficiently to achieving those outputs. A plan describing the strategy for predicting these outputs has been completed and peer reviewed. It provides a much more detailed discussion of the S&I project's activities.

Integration is aided by a computerized tracking system which follows the progress of each of the many individual research efforts within the research cooperatives. The system provides an adaptable means of organizing and summarizing specific information from a large number of projects. The tracking system's data base will be regularly updated to reflect the current status of all projects. That information, in conjunction with the flexibility of the

system's reporting capability, provides a means of addressing a wide variety of questions regarding research in progress.

Projects are evaluated by S&I for their potential contributions to program-wide outputs and for their role in supporting or rejecting hypothesized mechanisms of the action of air pollutants on trees and forests. These evaluations help to satisfy an S&I goal of focusing research on the most plausible hypotheses. Project evaluations are also important inputs to the research planning process. If the results of project evaluations indicate, for example, that important areas of research have been neglected, or that there is inadequate provision to provide information critical for certain synthesis activities, program and cooperative planning will need to address these omissions.

Synthesis is achieved through quantitative analyses and modeling of the many different kinds of data produced by the program. An approach based upon biological levels of organization distinguishes seedlings, whole mature trees, stands, and regions, and provides a structure to this diversity of data. The strategy of such an approach is two-fold. First, each level is being studied and analyzed in and of itself. Second, efforts are being made to synthesize information at one level to act as input to the next. This approach explicitly recognizes the simultaneity of physiological studies with ecological and regional studies.

The ability to project the response to alternative deposition scenarios will come from an understanding of the dynamics of trees and forests affected by air pollution. Forests are always dynamic and an understanding of dynamics has been, of course, a goal of much forestry and ecological research over the last several decades. The body of knowledge produced gives the FRP a sound starting point. However, many studies of the effects of pollution on forests have addressed effects on states of forests rather than on dynamics. This has

led to some confusion as, for example, when age is used as a competing explanatory variable with pollution. Pollution effects must be compared to normal overall stand dynamics, not just a single component such as age.

3.8 Quality Assurance

The goal of the Quality Assurance (QA) Project is to assure that Forest Response Program data are of known and sufficient quality to meet their intended use for the synthesis and integration of research results, leading to the assessment of atmospheric deposition effects on forest ecosystems. The following objectives are designed to achieve this goal:

1. Provide guidance, reinforcement, and resources to the investigators for the implementation of QA activities;
2. Assure comparability of research and QA activities across sites and over time;
3. Examine, evaluate, and adjust research and QA activities to assure continued compliance with standard or approved protocols and procedures; and
4. Provide evidence of research data quality through qualitative and quantitative evaluations.

Given the biological nature of FRP research and the number of sites conducting the research, there is a need for monitoring and maintaining data quality requirements and standardizing procedures. Additionally, the FRP should be consistent throughout the length of the project. For these reasons, the QA Project has established four QA Methods Manuals to provide guidance and standardized procedures for investigators. The manuals correspond to four basic research areas: Exposure Systems and Physiological Measurements; Site Classification and Field Measurements; Laboratory Analytical Techniques; and Experimental Design and Data Management. The QA Project has also established

basic guidance and QA requirements, including guidelines for developing QA Project Plans, in the national QA Implementation Plan and Data Quality Objectives document.

Due to the assessment and possible regulatory nature of the work, the results of the research may be challenged by the scientific and legal communities. Full documentation of procedures and results (with accompanying data quality information) will provide a scientifically and legally defensible position during controversy. Therefore, the FRP is committed to produce thorough documentation and sound QA practices.

The FRP must have an integrated QA program which begins with the assessment of the intended use of the data and, thereby, the data needed to support a decision. From this knowledge, decision makers can establish the level of quality needed to make the data usable, called Data Quality Objectives (DQOs). Given the level of data quality needed, the researcher designs the system of methods, protocols, quality control checks, responsibilities, and documentation procedures to produce the needed data, the quality of which is known, documented, and sufficient to meet its intended use. This system is documented in a QA Project Plan which must be approved by National Program Management before being implemented. The QA Staff organizes sample exchanges across projects and cooperatives to monitor precision, accuracy, and consistency within the program. In addition, the QA Staff will periodically audit research facilities to assure that investigators are following standardized or approved procedures. Quality assurance is ultimately documented in the results like all oth
er essential parts of a research project.

3.9 Interaction Among Program Components

Close coordination among the various parts of the FRP is essential if program-wide outputs are to be developed efficiently and on schedule. Cooperatives are dependent upon one another for data, services, and planning support. The following is a brief description of the major technical interactions required for program success. Managerial relationships are defined in the following section (4.0).

Because the cooperatives function with a common research strategy (described earlier in this section), many individual research projects dealing with the same S.Q. differ only by the species under study. Standard research protocols are used when possible. As common issues surface, specific arrangements are made to address them with an appropriate mechanism, e.g., shared funding of a research effort, a program-wide workshop, etc. While many of these arrangements are made through informal contacts among cooperative management, this coordination role will increasingly become the responsibility of the S&I project as it begins formulating specific pathways to achieving program-wide outputs.

The following list serves to illustrate the more significant interactions:

1. Inventory Data. The combined effort to access all available data useful to address S.Q.'s 1.1 and 1.2 is a prime example of interaction among FRP components. The NVS supports specific research efforts that address these questions for SFC, SCFC, and EHC. These projects, as well as the WCC's evaluation of inventory data sets, fit directly into the S&I objetive of providing evaluations of changes in forest condition and the role of non-air pollution factors in forest decline.

2. Data Management. The SFC and SCFC jointly fund a data management group at North Carolina State University that is responsible for gathering and

storing data from the principal investigators of these two cooperatives. The S&I project has overall responsibility for managing FRP central data bases and, in this capacity, interacts to assure that the North Carolina State University group's data are compatible with program-wide data management protocols. The NVS interacts with the cooperatives by funding projects designed to evaluate existing forest inventory and research data bases for specific growth patterns to help answer S.Q. 1.1 and 1.2.

While the QA project is conducting its central task of assuring data quality, the individual QA Specialists also serve an important role as "first-line" contact with the principal investigators for each of the research projects. This contact serves to keep both cooperative management and S&I current on progress within each research project. Knowing exactly when data are to be available and in what form is critical to the S&I task. An important communication link is maintained through this frequent interaction of QA staff and researchers.

3. Deposition Data. All cooperatives have the same need for atmospheric deposition data. The AEC provides this support in two ways: (1) providing deposition monitoring on intensive forest sites for SFC and SCFC; and (2) assisting all program components, but particularly S&I, in accessing existing deposition data bases and atmospheric models. This support function will become increasingly critical as the S&I and NVS begin spatial analyis of growth and deposition data.

4. Modeling. The S&I has overall responsibility for coordinating the prediction of regional responses of forests on a regional basis to atmospheric deposition. However, individual cooperatives and NVS are contributing to this effort. In particular, SFC is conducting modeling research on the spruce-fir ecosystem that will feed directly into S&I work.

5. Joint Funding. Where projects are of particular interest on a program-wide basis, joint funding among cooperatives is undertaken. The SCFC, SFC, and WCC are jointly funding research to evaluate exposure of large trees to pollutants. Developing appropriate methodology could help solve a major question: How can we extrapolate results from seedling experiments to mature trees?

6. NCASI. The forest products industry provides important contributions to the FRP in two ways; (1) technical support by NCASI staff who serve as advisors to the WCC, SFC, and SCFC, and by organizing technical workshops; and (2) financial support of individual research projects of particular interest to the forest products industry. This support has been a crucial element both in program planning and implementation.

In addition to the above internal interactions, the FRP maintains close working relationships with other organizations conducting work on forest response to atmospheric deposition. The Electric Power Research Institute is supporting a number of mechanistic studies on the forest types of direct interest to the FRP. Where possible, research efforts are co-located (SFC and SCFC). The data gathered by EPRI will be utilized as part of the FRP data base where appropriate. The WCC works closely with the California Air Resources Board (CARB) both in co-location of research sites and in the conduct of technical workshops and program planning. Other university and agency interactions occur daily throughout the FRP.

4.0 PROGRAM MANAGEMENT

The following sections describe the processes and procedures that will be used to administer and direct the Forest Response Program. They include Management Structure and Responsibilities, Planning and Funding, Monitoring, and Reviewing and Revising.

4.1 Management Structure and Responsibilities

The scope and complexity of the FRP requires a strong commitment by the participating agencies and NAPAP to an integrated system of management. The EPA and the Forest Service are both contributing substantial scientific and financial resources to this research program. Therefore, the FRP must have joint, centralized management.

To achieve that goal, EPA and the Forest Service have negotiated a broad Interagency Agreement for Jointly Managed Research on Effects of Atmospheric Deposition on U.S. Forests. It outlines a management structure for the national program that provides technical and fiscal direction and supervision through a strong central chain, while maintaining line authority for administering federal funds within and between agencies.

The FRP management structure consists of three levels: Federal Management Group (FMG), National Program Management, Research Cooperative Management. Appendix A lists names, addresses, and phone numbers of FRP management as of November 1, 1986. The flow of managerial and technical direction is illustrated in Figure 5.

Federal Management Group

Executive oversight of the Forest Response Program is the responsibility of the FMG. The FMG's specific responsibilities include:

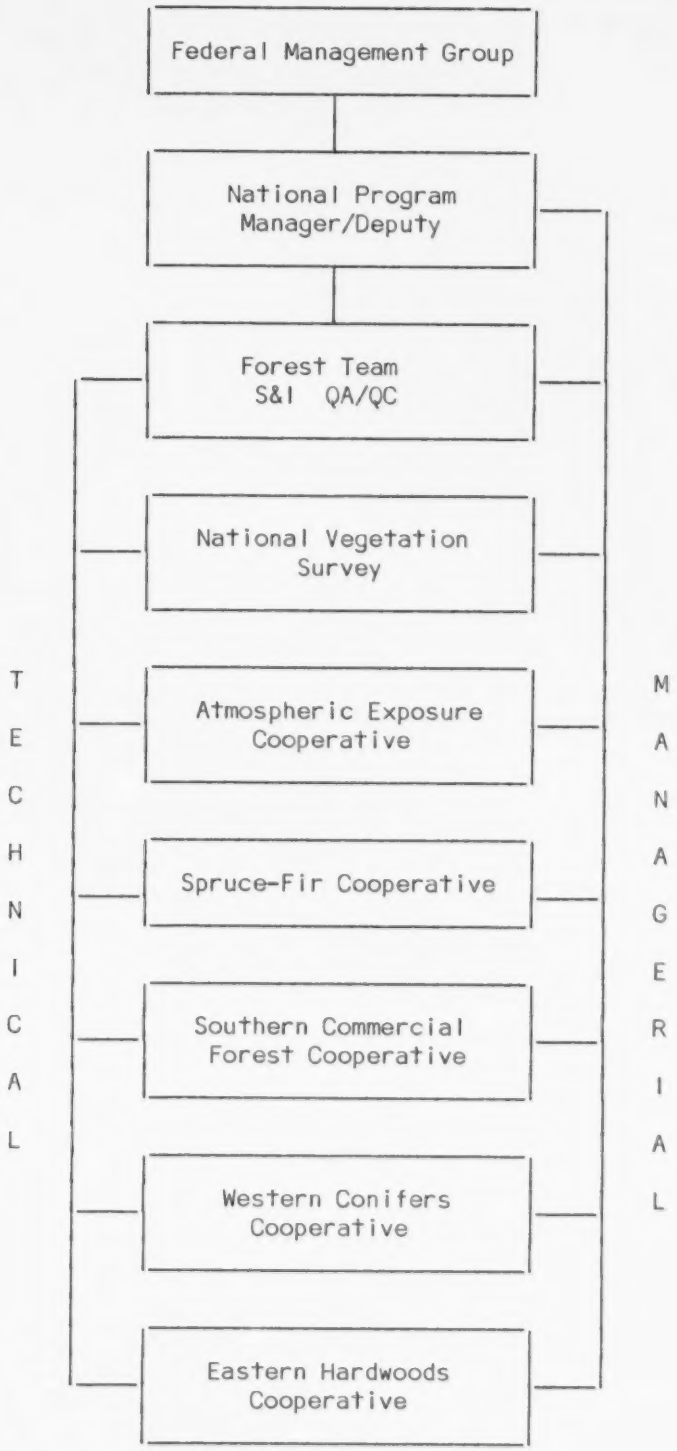

Figure 5. Managerial and technical lines of communication for the Forest Response Program.

1. Interpretation of policy to define broad research objectives, expected major outputs, and funding options for the research cooperatives;
2. Concurrence in selection of Research Cooperative Managers;
3. Definition of QA/QC and peer review requirements;
4. Periodic review of program management and implementation of corrective action as needed; and
5. Concurrence on research plans, and research proposals funded (both in-house and extramural) by the cooperatives.

National Program Management

The national program is managed by the National Program Manager (NPM), the Deputy National Program Manager (DNPM), and the Forest Team Leader (FTL). The NPM/DNPM are responsible for administering the program. Specific responsibilities of the NPM/DNPM include:

1. Managerial and policy liaison between FMG and Research Cooperative Managers, Task Group V, NAPAP leaders, federal/state agencies, and private industry;
2. Day to day coordination of program-wide activities.
3. Developing program budgets.
4. Annual peer review of research cooperatives and corrective action as appropriate.

The Forest Team Leader is responsible for integration of program results to meet national assessment needs through the Synthesis and Integration Project and administration of the Quality Assurance Program. Specific responsibilities include:

1. Technical direction of program-wide planning and research activities.

2. Manage the centralized Quality Assurance Program and assure compliance of cooperatives with QA protocols.
3. Manage the development of program-wide outputs and a centralized data base.
4. Conduct specialized assessment analyses requested by NAPAP that require integration and synthesis of results across forest types (regional or national assessments).

Research Cooperative Management

The Cooperative Managers will manage their research cooperatives in accordance with technical direction provided by national management. Specific responsibilities include:

1. Develop a research plan annually to guide research consistent with objectives specified by national program management;
2. Prepare Requests for Proposals;
3. Receive proposals and review proposals according to procedures established by the FMG, select the best proposals, and prepare funding recommendations for submission to NPM, DNPM, and FTL;
4. Provide technical direction to inhouse staff working within the cooperative;
5. Conduct annual technical reviews of individual projects;
6. Integrate research results for the cooperative to meet major objective and outputs specified by NPM, DNPM, and FTL;
7. Develop effective data base management with formats in common with other research cooperatives (where practicable) and the national data base management;

8. Develop and implement procedures consistent with QA/QC requirements specified by the FMG, NPM, DNPM, and FTL.

4.2 Planning and Funding

These two activities are so closely related within the FRP that they are combined here. The entire planning process ultimately results in implementation of research plans via funding decisions. The normal path to research funding is summarized in Figure 6. The Federal Management Group initiates the annual planning process by issuing a research directive to the NPM, DNPM, and FTL which identifies policy issues and provides overall program direction.

The research directive is the basis for development of the National Research Plan (this document) that is prepared jointly by the NPM, DNPM, and FTL. The national research plan outlines specific objectives and discusses the general approach to achieving them, and will discuss the plan for integrating results from the Research Cooperatives into major products.

Each program component has prepared a research plan that specifies the nature of the problems to be studied, reviews pertinent literature, analyzes alternative study approaches, proposes specific studies, and identifies extramural research needs. The plan specifies QA/QC procedures, data quality objectives, and data formats. Each plan has been peer reviewed by outside scientists before being submitted for approval by the national management and the FMG. Requests for proposals are prepared by the Cooperative Managers based on these research plans.

Research study proposals detail specific procedures that are to be used to execute specific studies identified in the cooperative research plan. They are peer reviewed for technical merit by the Cooperative Managers and Synthesis and Integration according to minimum requirements established by the FMG. The

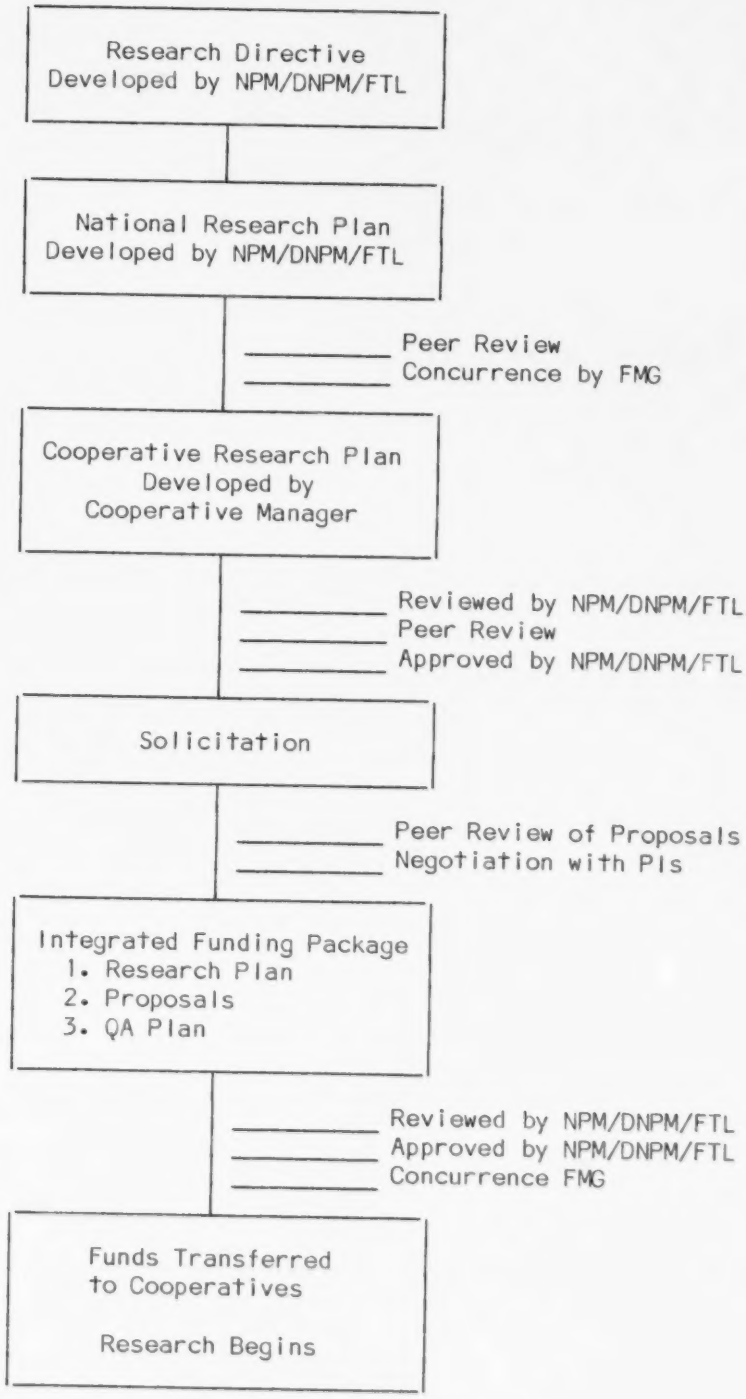

Figure 6. Forest Response Program planning and funding procedures.

Cooperative Manager and NPM/DNPM/FTL, working together, develop an integrated funding package consistent with guidance from the research directive, the national research plan, and the cooperative research plan.

The integrated funding package provides the basis for annual approval and release of research funds. It includes:

1. The cooperative research plan.
2. Approved research proposals.
3. Quality assurance plan.

Integrated funding packages recommended for approval by the NPM/DNPM/FTL to the FMG. On approval by the FMG, funds are dispersed to implement the research.

Requests for exceptions to this path for approval are considered on a case by case basis, but require advance approval of the NPM/DNPM/FTL and the FMG.

In fiscal year 1987, all Research Cooperatives will have completed their first planning and funding cycle. The planning schedule shown in Table 5 coordinates FRP planning so that all Cooperatives will be on the same schedule and funding can be provided to Principal Investigators before the research field season begins. The critical date in the schedule is October 1. This is the beginning of the fiscal year when the new budget is approved by Congress. It is appropriate to have Cooperative research plans and solicitations approved by this date so that new research can be solicited immediately. The February endpoint for the annual planning cycle was chosen so that researchers would have funds available to begin research at the beginning of the growing season. Other dates on the schedule were selected to accommodate the necessary national-level planning, program reviews, and grants administration.

Table 3. Annual Forest Response Program Planning Schedule

Activity	Date
Research directive prepared by FMG	03/01
National research plan	
Internal review	03/07
Peer review (if update necessary)	07/01
Completed and approved	08/14
Research cooperative research plans	
Reviewed by NPM/DNPM/FTL	08/01
Peer review	09/01
FMG concurrence	09/15
Approval for solicitation	10/01
Research proposals received and peer reviewed	12/15
Integrated funding package	
Reported by NPM/DNPM/FTL	01/15
Concurrence by FMG	02/01

4.3 Monitoring

Because of the number and diversity of components that comprise the Forest Response Program, it is critical that national management have the means to monitor the progress and current status of all research activities. Several monitoring mechanisms have already been instituted and others are planned.

Internal Communications and Project Tracking

A teleconference is held each week with the National Program Management and Cooperative Managers. It provides national management with a regular structured weekly opportunity to track research at the cooperative level and to check progress toward major milestones.

An electronic communcations system designed to rapidly update information and enhance communication is planned. Access to the system would be open to anyone in the program with a personal computer and a modem. Unexpected changes in meeting schedules or travel plans, for example, could be relayed rapidly. Other sections of the system could be updated regularly to provide current information on planning activities, research progress, and other pertinent topics.

It will specifically be the responsibility of the Forest Team Leader at ERL-C to track the progress of individual projets and their outputs required to complete major program products on time.

Quality Assurance Audits

Quality assurance audits are a powerful tool for monitoring the way research is conducted at the PI level. Audits are currently classified into four groups: Performance Evaluations (PEs), Technical Systems Audits (TSAs), Management Systems Audits (MSAs), and Audits of Data Quality (ADQs). These

audits are formal reviews of QA/QC activities to determine compliance with the QA Project Plan (and Research Plan) and national documentation. Audit reports provide: (1) reassurance to upper management that quality data are being produced (at a known cost); (2) periodic status reports on the program; and (3) identification of modifications and adjustments to data collection and analysis. Audits are conducted by the QA Staff, at least annually, the actual frequency of which is determined by the stage of the program, past performances, and the intended use of the data.

Audit reports are prepared by the QA Specialist and distributed to the investigators and the QA Coordinator. An audit report is distributed to the Cooperative Director, summarizing audit results by project or by group of projects. Problems are resolved as efficiently as possible by the QA Specialist. Should the QA Specialist not be able to resolve a problem, the QA Coordinator and Cooperative Director will review the problem. Should they also be unable to resolve the issue, the QA Project Leader will take the issue before the National Program Management for final resolution.

Peer Reviews

Peer reviews of research plans by scientists outside of the Forest Response Program are an important way to monitor the technical quality and relevance of the program's direction. A hierarchy has been established to review plans at the project, research cooperative, and national levels. Research plans submitted by principal investigators for individual projects are reviewed by the research cooperatives. Reviews of cooperative research plans are arranged by national management, but conducted by outside scientists. The peer review of the national research plan is also conducted by outside scientists and is arranged by the Federal Management Group.

4.4 Reviewing and Revising Program Direction

This document outlines the objectives of the Forest Response Program and the direction it will take during the early stages of implementation. As results from the initial studies become available, new insights may lead to changes in priorities and direction. Revisions will normally be accommodated during the continued planning and peer review process.

5.0 MAJOR PRODUCTS

The Forest Response Program will develop five major products over the next several years. These products will be developed from a synthesis of results from all components of the program. They are intended to provide policy makers with the best available information to answer the three policy questions basic to the program. Major products and their estimated completion dates are summarized in Table 4 and discussed below.

Table 4. Major products and estimated completion dates.

	Product	Estimated Completion Date
1.	Evaluation of changes in forest condition.	12/88
2.	Evaluation of non-air pollution factor in forest decline.	12/88
3.	Quantitative estimates of seedling response.	12/87 and annually
4.	Evaluation of S, N, and associated pollutants in forests.	04/89, 04/91
5.	Projection of responses under alternative deposition.	12/91

5.1 Evaluation of the Extent and Magnitude of Recent Changes in Forest Condition

All forests vary in space and time. Any effects of air pollutants must be studied against the natural patterns of forest change. Air pollution effects must be extracted from this background of natural variation. The intent of this output is to quantify the changes currently seen in forests. These changes are to be evaluated initially without any consideration of causes.

However, this evaluation will place an upper limit on changes that could have been caused by any factor, including air pollution.

5.2 Evaluation of the Role of Non-Air Pollution Factors in Growth Reduction and Visible Decline

Measured changes in forests must be evaluated to determine the role of natural and anthropogenic factors in producing those changes. Natural factors include the effects of normal stand dynamics, weather and climate, and pests and pathogens. Human factors include such practices as logging. The majority of the changes commonly seen in forests are caused by natural factors and forestry practices. Consequently, these effects must be well understood in order to define and evaluate effects of air pollution. Furthermore, any claim that a change is due to air pollution must take into account any change caused by background factors.

5.3 Quantitative Estimates of Seedling Response to Sulfur, Nitrogen, and Associated Pollutants at Ambient Conditions

Although an ultimate goal of the FRP is to understand the effect of various atmospheric pollutants on mature trees and stands of trees, much of the early research is on seedlings. Virtually all of the controlled experimental work is on seedlings. A major task of the FRP is to extrapolate data from seedlings to responses of mature trees. However, seedling information will provide useful data early in the program before the extrapolation effort begins. The seedling response output will consist of annual reports on the results of the seedling experiments interpreted consistently with our knowledge of their projectability.

5.4 Evaluation of the Roles of Sulfur, Nitrogen, and Associated Pollutants in Forest Effects

The S&I Project has combined a "levels-of-organization" approach with a variety of statistical analyses and modeling techniques to determine the roles of sulfur, nitrogen, and associated pollutants in forest effects. The basic concept is to combine information gained from physiological studies on the mechanism of action of pollutants with survey analyses of forest condition and atmospheric deposition. We are planning a structured diversity of models to develop meaningful data for this output.

5.5 Projection of Responses Under Alternative Deposition Scenarios

The previous output is designed to understand the dynamics of forests faced with atmospheric deposition. This understanding of dynamics will provide the basis for a series of projection models, both statistical and computer based. Work on this output will interface with other large scale assessment programs such as the Resources Planning Act Program of the Forest Service and will allow the evaluation of different control/deposition scenarios.

Literature Cited

Abrahamsen, G. 1980a. Acid precipitation, plant nutrients, and forest growth. pp. 58-63. In: Ecological Impact of Acid Precipitation. D. Drablos and A. Tollan (eds.). Proc. of an International Conference, Sandefjord, Norway. SNSF Project. Oslo-As, Norway.

Abrahamsen, G. 1980b. Effects of acid precipitation on soil and forest: Leaching of plant nutrients, p. 196. In: Ecological Impact of Acid Precipitation. D. Drablos and A. Tollan (eds.). Proc. of an International Conference, Sandefjord, Norway. SNSF Project. Oslo-As, Norway.

Abrahamsen, G. 1980c. Impact of atmospheric sulfur deposition on forest ecosystems. pp. 397-416. In: Atmospheric Sulfur: Environmental Impact and Health Effects. D. S. Shringer, C. R. Richmond, and S. E. Lindberg (eds.). Ann Arbor Science, Ann Arbor, Michigan.

Abrahamsen, G., and B. Tviete. 1983. Effects of air pollutants on forest growth. pp. 199-219. In: Ecological Effects of Acid Deposition. National Swedish Environment Protection Board. Report PM 1626. Solna, Sweden.

Babich, H., and G. Stotzky. 1979. Environmental factors that influence the toxicity of heavy metal and gaseous pollutants to microorganisms. Crit. Rev. Microbiol. 8:99-145.

Bjor, K., and O. Teigen. 1980. Effects of acid precipitation on soil and forest. 6. Lysimeter experiment in greenhouse, pp. 200-201. In: Ecological Impact of Acid Precipitation. D. Drablos and A. Tollan (eds.). Proc. of an International Cnference, Sandefjord, Norway. SNSF Project. Oslo-As, Norway.

Clark, R. K., and S. C. Clark. 1981. Floristic diversity in relation to soil characteristics in a lead mining complex in the Pennines, England. New Phytol. 98:799-815.

Fowler, D., J. N. Cape, I. A. Nicholson, J. W. Kinnaird, and I. S. Patterson. 1980. The influence of a polluted atmosphere on cuticle degradation in Scots pine. In: Ecological Impact of Acid Precipitation, Proceedings of an International Conference. D. Drablos and A. Tollan, eds. SNSF Project, Oslo, Norway.

Foy, C. D. 1974. Effects of aluminum on plant growth. pp. 601-642. In: The Plant Root and Its Environment. A. W. Carson (ed.). University Press of Virginia, Charlottesville.

Freidland, A. J., A. H. Johnson, and T. G. Siccama. 1984. Trace metal content of the forest floor in the Green Mountains of Vermont: Spatial and temporal patterns. Water, Air, and Soil Pollution 21:161-170.

Friedland, A. J., A. H. Johnson, T. G. Siccama, and D. L. Lader. 1984a. Trace metal profiles in the forest floor of New England. Soil Sci. Soc. Am. J. 48:422-425.

Friedland, A. J., R. A. Gregory, L. Karenlamp, and A. H. Johnson. 1984b. Winter damage to foliage as a factor in red spruce decline. Can. J. For. Res. 14:963-965.

Johnson, A. H. 1983. Red spruce decline in the northeastern U.S.: Hypotheses regarding the role of acid rain. JAPCA 33(11):1049-1054.

Haman, F. 1977. Effects of percolating water with graduated acicity upon the leaching of nutrients and the changes in some chemical properties of mineral soils. Journal of the Scientific Agricultural Society of Finland 49(4):250-257.

Hoffman, W. V., Jr., S. E. Lindbug, and R. R. Turner. 1980. Precipitation acidity: the role of the forest canopy in acid exchange. J. Environ. Qual. 9:95-100.

Huete, A. R., and J. G. McColl. 1984. Soil cation leaching by "acid rain" with varying nitrate-to-sulfate ratios. J. Environ. Qual. 13:366-371.

Huttunen, S., and K. Laine. 1983. Effects of airborne pollutants on the surface wax structure of Pinus sylvestris needles. Ann. Bot. Fenn. 20:79.

Jackson, D. R., W. J. Selvidge, and B. S. Ausmus. 1978. Behavior of heavy metals in forest microcosms. I. Transport and distribution among components. II. Effects on nutrient cycling processes. Water, Air Soil Poll. 10:3-18.

Johnson, D. W., J. Turner, and J. M. Kelly. 1982. The effects of acid rain on forest nutrient status. Water Resources Res. 18:449-461.

Kramer, P. J., and T. T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, New York. 811 pp.

Lee, J. J., and D. E. Weber. 1982. Effects of sulfuric acid rain on major cation and sulfate concentrations of water percolating through two model hardwood forests. J. Environ. Qual. 11:57-64.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson. 1977. Biogeochemistry in a forested ecosystems. Springer-Verlag, New York. Final Report to Electric Power Research Institute, Palo Alto, California, December 1984, 53 p.

McLaughlin, S. B., and D. S. Shriner. 1980. Allocation of resources to defense and repair. In: Plant Disease, J. G. Horsfall and E. B. Cowling (eds.), Academic Press, New York, Chapter 22.

McLaughlin, S. B., and R. K. McConathy. 1983. Effects of SO_2 and O_3 on ^{14}C-photosynthate allocation. Plant Physiol. 73:630.

Prinz, B., G. H. M. Krause, and H. Stratman. 1982. Forest damage in the Federal Republic of Germany. LIS Report No. 28. Land Institute for Pollution Control, Landesanstalt fur Immissionsschutz des Landes Nordrhein-Westfalen. Essen. Wallneyer Strabe 6, Federal Republic of Germany. 145 pp. (C.E.G.B. Translation No. T14240)

Rolfe, G. L., and F. A. Bazzaz. 1975. Effect of lead contamination on transportation and photosynthesis of loblolly pine and autumn olive. For. Sci. 21:33-35.

Ruhling, A., and G. Tyler. 1973. Heavy metal pollution and decomposition of spruce needles litter. Oikos 24:402-416.

Scherbatskoy, T., and R. M. Klein. 1983. Response of spruce and birch foliage to leaching by acidic mist. J. Environ. Qual. 12:189-195.

Schier, G. A. 1984. Seedling growth in New Jersey Pine Barrens soil treated with "acid rain." Submitted to J. Environ. Qual., Paper presented at NAPAP Peer Review, Asheville, North Carolina, November 13-16, 1984.

Schier, G. A. 1985. Response of red spruce and balsam fir seedlings to aluminum toxicity in nutrient solutions. Can. J. For. Res. 15:29-33.

Shafer, S. R., L. F. Grand, and R. I. Bruck. 1985. Formation of ectomycorrhizae on Pinus taeda L. seedlings exposed to simulated acid rain. Can. J. For. Res. 15:66-71.

Sheffield, R. M., N. D. Cost, W. A. Bechtold, and J. P. McClure. 1985. Pine growth reductions in the Southeast. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina. Resource Bulletin SE-83. 112 pp.

Shriner, D. S. 1983. Leaf responses to acid deposition. In: The acidic deposition phenomenon and its effects. E-2 effects on vegetation.

Critical Assessment Review Papers, Volume II, Section 3.2.1. EPA A-600/8-0163.

Soikkeli, S., and L. Karenlampi. 1984. The effects of nitrogen fertilization on the ultrastructure of mesophyll cells of conifer needles in northern Finland. European J. Forest Pathology (in press).

Stuanes, A. O. 1980. Effects of acid precipitation on soil and forest. Release and loss of nutrients from a Norwegian forest soil due to artificial rain of varying acidity. pp. 198-199. In: Ecological Impact of Acid Precipitation. D. Drablos and A. Tollan (eds.). Proc. of an International Conference, Sandefjord, Norway. SNSF Project. Oslo-As, Norway.

Tisdale, S. L., and W. L. Nelson. 1975. Soil Fertility and Fertilizers. MacMillan, New York. 694 pp.

Tukey, H. B., Jr. 1970. The leaching of substances from plants. Ann. Rev. Plant Physiol. 21:305-324.

Tyler, G. 1975. Heavy metal pollution and mineralization of nitrogen in forest soils. Nature 255:701-702.

Ulrich, B. 1980. Production and consumption of hydrogen ions in the ecosphere. pp. 255-282. In: Effects of Acid Precipitaiton on Terrestrial Ecosystems. T. C. Hutchinson and M. Havas (eds.). Plenum Press, New York. pp. 255-282.

Weetman, G. F., and R. M. Fournier. 1984. Ten-year growth and nutrition effects of a straw treatment and of repeated fertilization on jack pine. Can. J. For. Res. 14:416-423.

Wood, T., and F. H. Bormann. 1975. Increases in foliar leaching caused by acidification of an artificial mist. Ambio 4(4):169-171.

Wong, M. H. 1982. Metal co-tolerance to copper, lead, and zinc in Festica rubra. Envir. Res. 29:42-47.

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APPENDIX B

Data Quality Objectives for the National Plan

Following is a brief explanation of Forest Response Program Data Quality Objectives (DQOs), extracted from the draft DQO document. These DQOs are separated into Experimental DQOs, providing guidance in the design of experiments, and Measurement DQOs, providing quantitative guidance for individual variables measured in the FRP.

Experimental DQOs

Within the Forest Response Program, experimental DQOs specify the statistical characteristics of experiments required to evaluate and accept or reject proposed mechanisms. In this respect, DQO's are directly linked to the decision criteria established for each of the program's scientific questions. Program level decisions regarding particular mechanisms will most likely be based on results from a variety of experiments. It is not always possible, however, to combine the results of varied experiments into a single comprehensive statistical test. Decisions must therefore be made on the basis of scientific judgment in light of all available evidence. DQO's seek to assure that experiments are useful for decision making.

Experiments within the FRP are encouraged to be statistically conservative. In other words, relatively small responses in critical variables can and should indicate the need for further study in the absence of clear contradictory information.

Experimental DQOs are expressed in terms of threshold level, level of significance (alpha), and power or weight of evidence:

1. Threshold level is defined as a response in the critical variable expressed as an absolute or percent change or as a threshold level, that we are interested in detecting. This response should be related to biological significance. Biological significance will be determined from the literature and from the consensus of experts in the appropriate fields. Investigators involved in the FRP will be a major source of this information.

2. Level of significance is defined as the probability of incorrectly claiming a significant difference when the difference actually does not exist. The conservative approach required of projects is to accept a lower level of significance than is normally considered appropriate so that marginally significant evidence will be taken as a reason to continue exploration of the alternative. No mechanism will be accepted or rejected solely on the basis of a simple or single statistical test, but an explicit significance level is essential to investigators as a target in designing their experiments. In all cases, investigators should also report the actual level of significance achieved so that it can be weighed in evaluating results.

3. The power or weight of evidence in an experiment is the probability of rejecting a proposed mechanism when in fact that proposed mechanism is wrong. Power is a function of how much data (e.g., sample size) has been gathered, and how much noise (i.e., variability) is in the system. Therefore, if you have a certain amount of noise exists and you want strong evidence from the experiment, you may have to increase the sample size and/or modify the experimental design.

Both the actual significance level and actual power achieved should always be reported since the weight of evidence is dependent on experimental design. Experiments should be be designed specified objectives. Following is an example of experimental DQOs for scientific question 2.1.

SCIENTIFIC QUESTION 2.1

Question:

What is the effect of sulfur and/or nitrogen pollutants on forests through the mechanisms of:

(1) Direct toxicity to roots, mycorrhizae, or soil microbial populations by mobilized metals in acidified soil water;

(2) Nitrogen toxicity to mycorrhizae;

(3) Increased leaching of soil nutrients resulting in reduced nutrient availability.

Decision Criteria:

We will conclude that the mechanism of direct metal toxicity to roots, mycorrhizae, or soil microbial populations is plausible and warrants further research if a representative sample of soils associated with a relevant forest type experiences increased mobility of metals when exposed to a spatially representative sample of ambient and greatly above ambient sulfur and nitrogen derived pollutants in realistic temporal sequence under representative environmental conditions.

We will conclude that the mechanism of nitrogen toxicity to mycorrhizae is plausible and warrants further research if a representative sample of soils associated with a relevant forest type experience increased nitrogen concentration when exposed to a spatially representa-

tive sample of ambient or greatly above ambient nitrogen compounds in realistic temporal sequence under representative environmental conditions.

We will conclude that the mechanism of leaching nutrients from the rooting zone is plausible and warrants further research if a representative sample of soils associated with a relevant forest type experience increased nutrient leaching when exposed to a spatially representative sample of ambient and greatly above ambient sulfur and nitrogen derived pollutants in realistic temporal sequence under representative environmental conditions.

Data Quality Objective Guidelines:

The biologically significant response in aluminum mobility is the threshold at which aluminum concentrations in soil solution become toxic. Studies of aluminum toxicity reviewed by Abrahamsen and Tveite (1983) suggest that concentrations of 80 to 160 mg Al l^{-1} in solution are required to damage the roots of forest tree species. Most of the species studied by McCormick and Steiner (1978) were unaffected by solution concentrations of less than 80 Mg Al l^{-1} (the exception was a Populus species). Working specifically with red spruce, Schier (1985) found symptoms of aluminum toxicity to roots at 50 mg Al l^{-1}. The aluminum toxicity threshold, however, depends on more than just aluminum concentration; the Ca:Al ratio is also important. Ulrich (1983) discussed this ratio and concluded that aluminum injury is more likely when Ca:Al < 1.0 in the soil solution. The finding was supported by Abrahamsen (1984) who found damage to Norway spruce from only 20 mg Al l^{-1} with a Ca:Al ratio well below 1.0. Therefore, the following threshold levels will be used to address the decision criterion for aluminum:

50 mg Al l^{-1} when Ca:Al $\geq$ 1.0

20 mg Al l^{-1} when Ca:Al < 1.0

The suggested significance level for this area of research is alpha = 0.05 and suggested power objective of 1 - beta = 0.80, depending on the experimental design and the specific system within which you are testing.

Measurement DQOs

The Quality Assurance Management Staff of the EPA has defined guidelines and specifications for determining data quality objectives (DQOs) for environmental research. Ideally, DQOs are defined by five characteristics of the data which quantify where possible: precision, accuracy, representativeness, completeness, and comparability. These characteristics are briefly defined below:

- Precision and accuracy: the amount of variability and bias, respectively, inherent in a given data set. Precision is the variation among repeated measurements of the same variable. Accuracy is the difference between the "true" value of a variable and an estimate of the "true" value based on sample data.
- Representativeness: the degree to which the data collected accurately reflect the population being sampled.
- Completeness: the amount of data that is successfully collected with respect to that amount intended in the experimental design. Missing data may reduce the precision of estimates, introduce bias, and thus lower the level of confidence in the conclusions.
- Comparability: the ability to combine data from different sources into a single data set. "Comparable" data from different sources can be combined

into one data set when the sources had similar objectives (= intended use) and measured the same variables using similar methods.

The use of precision, accuracy, representativeness, completeness, and comparability requirements as guidance or management tools is, of course, limited. However, they are very important factors in the determination of the "quality" of a data set and should be acknowledged. True management tools for the Forest Response Program will consist of guidance in the form of experimental DQOs.

The elements of measurement DQOs in the Forest Response Program (precision, accuracy, representativeness, completeness, and comparability) are consistent with their definitions. Because of the size and complexity of the program, little attempt is made to be specific with this guidance at this point without the context of individual variables:

1. Precision and Accuracy. Precision and accuracy limits apply to specific variable measurements taken in the Forest Response Program. These limits are founded on the estimated "effect level" (i.e., at what level is the quality of the data compromised by a lack of precision or accuracy). Precision and accuracy limits apply to measurement error only, since sampling error fluctuates according to experimental design which cannot be fixed for the entire program. Hence, the terminology "repeated measurement error" for precision and "accuracy tolerance" for accuracy.

   Precision and accuracy are tested in the field and laboratory by repeated measurements and comparisons with true values, respectively. Many procedures which measure precision and accuracy are standard in laboratories (duplicates, standards, blanks) but developmental in field situations. The Forest Response Program Quality Assurance Methods Manuals detail all required checks for precision and accuracy with required

frequency (Evans and Dougherty, 1986; Robarge and Fernandez, 1986; Zedaker and Nicolas, 1986; Baes et al., 1986).

2. Representativeness. In general, the success of the Forest Response Program rests on the ability to infer the condition of forests across the nation from research conducted in small pieces throughout. Given this constraint, representativeness is a concern for all data collected, both experimental and survey.

   The representativeness of the experiment or the ability to extrapolate experimental results to field responses is a major concern in the Forest Response Program. Given that concern, the program emphasizes the concept of a "population of inference" where an experimental sample is inferred to a population of interest. Identification and justification of the population of inference is a requirement in outlining experimental design (Baes et al., 1986).

   Representativeness of field plots or the ability to imply forest conditions from research plots is also a major concern. Zedaker and Nicolas (1986) outline procedures for determining plot size and shape to insure this representativeness. For example, they determined that 400 square-meter rectangular plots located along contours, stratified by elevation, are appropriate in mountainous spruce-fir forests. In less diverse forests, smaller plots without stratification by elevation may be sufficient. The selection of appropriate plot size and design are carefully reviewed.

3. Completeness. Ideally, 100% of the intended samples are collected and successfully analyzed. In reality, some samples cannot be collected, as some may be lost or contaminated. The investigators in the Forest Response Program have concluded that the final database of an experiment

include 80% of the amount originally projected in order to ensure valid conclusions. Most experimental designs were established with that limit in mind when calculating sample size. Failure to produce 80% of the projected amount of data after verification and validation in any project will indicate the need for a close examination of the uses of that data.

4. Comparability. Concurrent with representativeness, the Forest Response Program is concerned with comparability of data from one research site to another (where appropriate). A program of this magnitude sees many investigators working on similar or identical hypotheses. Given the need to integrate research across the program (see the Synthesis and Integration Plan for the Forest Response Program), the Quality Assurance Program established four Methods Manuals to guide investigators in areas where comparability is crucial (e.g., measuring the same variables). This is not to imply that there are identical research projects within the Forest Response Program. Some variation between projects is desirable to guard against duplication of biases. Quality assurance procedures such as interlaboratory exchanges of samples and joint training exercises will be used to monitor and quantify comparability between sites.

Table B1 shows Measurement DQOs which apply to scientific question 2.1, from the earlier example. This table is extracted from the national DQO document. Any reference to the values presented should be made to the national DQO document.

Table B1. Measurement DQOs which apply to Scientific Question 2.1 (from National DQO Document).

Variables	Techniques	Measuring Units	Reporting Units	Expected Range	Repeated Measurement Error at Lower Limit	Repeated Measurement Error at Upper Limit	Measurement Accuracy Tolerance
Soil Physical							
Soil Moisture	gravimetric	grams	% mass	0-60	± 5%	± 5%	5%
Soil Bulk Density	core	grams/cc	mg/m^3	*	na	na	na
Water Content	gravimetric	grams	% (w/w)	na	na	na	na
% sand/silt/clay	PSA	time	%	*	10% (cv)	10% (cv)	na
Organic Matter	LOI	grams	%	0-95	± 50% (cv)	± 5% (cv)	5%
Soil Chemical							
pH by H_2O	meter	pH units	0.01 pH units	3.00-7.00	± .01	± .01	na
by $CaCl_2$	meter	pH units	0.01 pH units	3.00-7.00	± .01	± .01	na
by KCl	meter	pH units	0.01 pH units	3.00-5.00	± .01	± .01	na
Adsorption Capacity	*	*	mg/kg	50-100	± 20%	± 5%	5%
Extractable Anions:	extraction	*	mg/kg	20-300	± 20%	± 5%	5%
Orthophosphate	"Bray I" double acid	concentration	mg/kg	*	± 20%	± 5%	na
Sulfate	extraction	gS/ml entr.	mg/kg	*	± 20%	± 5%	na
Exchangeable Bases:							
- Ca	NH_4Cl extract.	µg/ml extr.	.01 ccmole(+)/kg	0.05-20.00	± .05	± 1.00	na
- Mg	NH_4Cl extract.	µg/ml extr.	.01ccmole(+)/kg	0.03-9.00	± .03	± .50	na
- K	NH_4Cl extract.	µg/ml extr.	.01 ccmole(+)/kg	0.05-6.00	± .05	± .30	na
- Na	NH_4Cl extract.	µg/ml extr.	.01 ccmole(+)/kg	0.05-1.00	± .05	± .05	na
Exchangeable Acidity:							
- Al	KCl extract.	µg/ml extr.	.01 ccmole(+)/kg	0.10-18.00	± .05	± 1.00	na
- H	KCl extract.	µg/ml extr.	.01 ccmole(+)/kg	0.10-18.00	± .05	± 1.00	na
Total EA	KCl extract.	µg/ml extr.	.01 ccmole(+)/kg	0.10-30.00	± .05	± 1.00	na
C.E.C.	calculation	na	ccmole(+)/kg	3.00-80.00	± 20	± 4.00	na
Extractable Metals:							
- Fe	HCl extract.	concentration	mg/kg	10-100	± 1	± 5	na
- Zn	HCl extract.	concentration	0.1 mg/kg	1.0-10.0	± 0.1	± 5.0	na
- Cu	HCl extract	concentration	0.1 mg/kg	1.0-10.0	± 0.1	± 0.5	na
- Pb	HCl extract.	concentration	0.1 mg/kg	0.5-20.0	± 0.1	± 1.0	na
- Cd	HCl extract.	concentration	0.1 mg/kg	0.1-3.0	± 0.1	± 0.2	na
- Ni	HCl extract.	concentration	0.1 mg/kg	0.1-2.0	± 0.1	± 0.1	na
- Mn	HCl extract.	concentration	mg/kg	10-100	± 1	± 5	na
Soil NH_4			0.1 mg/kg	1.0-20.0	± 0.5	± 15%	10%
			0.1 kg/ha/time	10.0-100.0	± 2.0	± 15%	10%
Soil NO_3^-N			0.1 mg/kg	1.0-20.0	± 0.5	± 15%	10%
			0.1 kg/ha/time	1.0-100.0	± 2.0	± 15%	10%
NO_2^-N Loss			0.1 µg/kg/day	0.1-200.0	± 0.1	± 50%	*
			0.1 kg/ha/month	0.1-10.0	± 5.0	± 50%	*

References

Abrahamsen, G., and B. Tveite. 1983. Effects of air pollutants on forest growth. pp. 119-219. In: Ecological Effects of Acid Deposition. National Swedish Environment Protection Board. Report PM1636. Solna, Sweden.

Abrahamsen, G. 1984. Effects of acidic deposition on forest soil and vegetation. Phil. Trans. R. Soc. Land. 305:369-382.

Baes, C. F., R. J. Olson, K. Riitters. 1986. Quality Assurance Methods Manual for Site Classification and Field Measurements. NCSU Acid Deposition Program, Raleigh, NC. 90 pp.

Evans, L. S., and P. Dougherty. 1986. Quality Assurance Methods Manual for Exposure Systems and Physiological Measurements. NCSU Acid Deposition Program, Raleigh, NC. 97 pp.

McCormick, L. H., and K. C. Steiner. 1978. Variation in aluminum tolerance among six genera of trees. For. Sci. 24:565-568.

Robarge, W., and I. Fernandez. 1986. Quality Assurance Methods Manual for Laboratory Analytical Techniques. NCSU Acid Deposition Program, Raleigh, NC.

Schier, G. A. 1985. Response of red spruce and balsam fir seedlings to aluminum toxicity in nutrient solutions. Can. J. For. Res. 15:29-23.

Ulrich, B. 1983. An ecosystem oriented hypotheses on the effect of air pollution on forest ecosystem. pp. 221-231. In: Ecological Effects of Acid Deposition. National Swedish Environment Protection Board. Report PM1636. Solna, Sweden.

Zedaker, S., and N. S. Nicholas. 1986. Quality Assurance Methods Manual for Site Classification and Field Measurements. NCSU Acid Deposition Program, Raleigh, NC. 90 pp.